Flanders
State of
the Art

00_128_16
FH reports

Coastal Morphology at Mariakerke

Final Report

DEPARTMENT
MOBILITY & PUBLIC WORKS

www.flandershydraulics.be

Coastal Morphology at Mariakerke

Final Report

Dan, S.; Vos, G.; Nguyen, D.; Montreuil, A-L.; Verwaest, T.

Flanders Hydraulics

Flanders
State of the Art

Cover figure © The Government of Flanders, Department of Mobility and Public Works, Flanders Hydraulic

Legal notice

Copyright and citation

D/2023/3241/075

This publication should be cited as follows:

Dan, S.; Vos, G.; Nguyen, D.; Montreuil, A-L.; Verwaest, T. (2023). Coastal Morphology at Mariakerke: Final Report. Version 3.0. FH Reports, 00_128_16 Flanders Hydraulics: Antwerp

Document identification

Customer:	MDK – Coastal Division	Ref.:	WL2023R00_128_16
Keywords (3-5):	Coastal morphology, beach and shoreface nourishment		
Knowledge domains:	Coastal protection>Coastal protection against erosion>Morphodynamics soft coastal defence>Literature and desktop study, in-situ measurements, numerical modelling		
Text (p.):	65	Appendices (p.):	4
Confidential:	☒ No	☒ Available online	

Author(s):	Dan, S.

Control

	Name	Signature
Reviser(s):	Verwaest, T.	Getekend door:Toon Verwaest (Signatur Getekend op:2023-03-31 12:22:50 +02:0 Reden:Ik keur dit document goed Toon Verwaest
Project leader:	Dan, S.	Getekend door:Sebastian Dan (Signature Getekend op:2023-03-31 12:37:05 +02:0 Reden:Ik keur dit document goed Sebastian Dan Vlaanderen

Approval

Head of Division:	Bellafkih, K.	Getekend door:Abdelkarim Bellafkih (Sig Getekend op:2023-03-31 13:29:28 +02:0 Reden:Ik keur dit document goed Abdelkarim Bellafkih

CERTIFIED ISO 9001

Abstract

The monitoring of the pilot nourishment executed at Raversijde - Mariakerke coastal area for comparing the morphological response to a combined beach and shoreface nourishment and to a beach nourishment took place from the start of the pilot nourishment in 2013 until 2018. Comprehensive data sets containing topographical (LIDAR and beach profiles) and bathymetrical (single and multibeam) measurements carried out at the study zone area have been analysed in order to evaluate the efficiency of the nourishments. Large part of the deployed sand is still in the area three years after the nourishment was carried out. The morphological trends show erosion in the intertidal beach, accumulation on the dry beach and re-organization of the shoreface nourishment into one or two submerged sand bar. Numerical modelling proved that this sand bar attenuates the wave height during stormy events both at low and high tide. The large space created south-west from the Ostend port through its extension in 2011 accommodates much of the sand eroding from the two coastal areas of the pilot site. The shoreline advanced towards the sea immediately after the nourishments and it maintains similar position after three years. The dominant process for the beach evolution was the cross-shore transport immediately after execution, but alongshore transport became dominant on the medium and long term and it was calculated to have a net rate of 150 000 to 200 000 m^3 in the north-east direction.

Contents

List of Tables

List of Figures

1 Introduction

1.1 The project

Within the framework of the Master Plan for Coastal Safety (Afedeling Kust 2011) the Flemish Government aims to reinforce all weak coastal sections in order to meet the required safety levels to respond to a storm-event with a return-period of 1 000 years till the year 2050. To protect the coast against storm induced flooding in the context of the anticipated acceleration of the sea level research is needed on sustainable engineering and the creative use of soft coastal protection measures, as alternative to the traditional ones. Typically, most of the nourishment at the Belgian coast are performed by placing the sand on the dry and intertidal beach. However, sand placed on the shoreface (-1.00 to -5.00 m TAW) can provide strength to the coast and less disturbance of the coastal system. In order to test this hypothesis, the zone of Mariakerke, one of the weakest links in terms of protection against storms, was chosen as the most suitable for the execution of a full-scale experiment on shoreface nourishments.

1.1.1 Objective

The project aims the assessment of the beach response to a combined beach and shoreface nourishment and to a beach nourishment alone, in order to investigate if underwater nourishments can reduce maintenance load, thus extending the lifetime of beach nourishment along the Flemish coast, without compromising coastal safety.

1.1.2 Experiment

The experiment consists on the execution and monitoring of a combined beach and shoreface nourishment over a coastal stretch and the comparison of an adjacent coastal stretch where only a beach nourishment is constructed (Figure 1). For the comparison an integrated approach including field measurement campaigns, video-monitoring, morphological numerical modelling and the definition and evaluation of a number of morphological indicators is adopted throughout the duration of the project. The profiles used as reference for monitoring are located at Raversijde-east coastal area, section 100 (beach nourishment only), and at Mariakerke coastal area, section 104 (combined beach and shoreface nourishment). A large beach nourishment was conducted within coastal sections 97 to 106 (872 100 m^3) and a shoreface nourishment within coastal sections 102 to 108 (303 800 m^3).

1.2 The assignment

The project “Alternatieve onderhoudsmatregelen voor strandsuppleties: monitoring van een pilootsuppletie in Mariakerke” – “Alternative maintenance measures for beach nourishment: monitoring of a pilot site” was commissioned by MDK Coastal Division[1] to Flanders Hydraulics (FH). Antea Group and Vrije Universiteit Brussels were contracted by FHR to assist in the assessment of the full-scale experiment.

The morphology of the pilot site and the evolution of the system in the last decade was studied and discussed in the first report, D1, (Silva *et al.*, 2016). This included a general overview of the project site, of the pilot nourishment, the delineation of an approach for the assessment of its efficiency and the presentation of the available datasets in the form of a data timeline including the hydrodynamic actions, the timings of the nourishments, the field campaigns, the topographic and bathymetric surveys. The design and choice of suitable methodologies for beach volumes calculation and update of morphological historical figures and trends, including the indication of the nourishment volumes applied, were set in such a way that they are fully compatible with previous analysis at the Flemish coast. Results of the morphological evolution and volume changes within Raversijde-east and Mariakerke coastal areas during the last decade, until 2015, therefore, before and after the pilot nourishment were presented. A number of morphological indicators were established and some of them estimated (depth of closure, intertidal and dry beach width).

The implementation of the morphological model, XBeach, at the project site was presented in the second report, D2 (Silva *et al.*, 2017). Furthermore, in that report, a number of three storms were characterized and compared. The short term response of the morphology to the pilot nourishment based on the available data was discussed. The procedure of model set-up, sensitivity analysis, calibration and validation was presented. As well as the modelling strategy which included the set-up in 1D, quasi-2D and finally 2D modes. The 2D simulations were performed over an area broader than Raversijde-east and Mariakerke coastal areas, aiming the inclusion of processes occurring in between adjacent coastal areas.

In the third report combining deliverables D3 and D4, the methodology studied and defined in the first delivered report is used to discuss the morphology evolution at the beach and shoreface after a longer time scale after the nourishment was constructed. The analysis is focused on the period 2015 - 2017. It includes the evaluation of the morphological changes and of the volumetric changes within pre-defined areas of analysis. Furthermore, the analysis of the profiling data, whose acquisition was initiated in September 2015 is also done.

In the present report, which is the final report of the project the morphological changes, volume differences, sediment transport and efficiency of the nourishments are presented and discussed for the entire time period for the project 2013 to 2018.

[1] Maritieme Dienstverlening en Kust – afdeling Kust

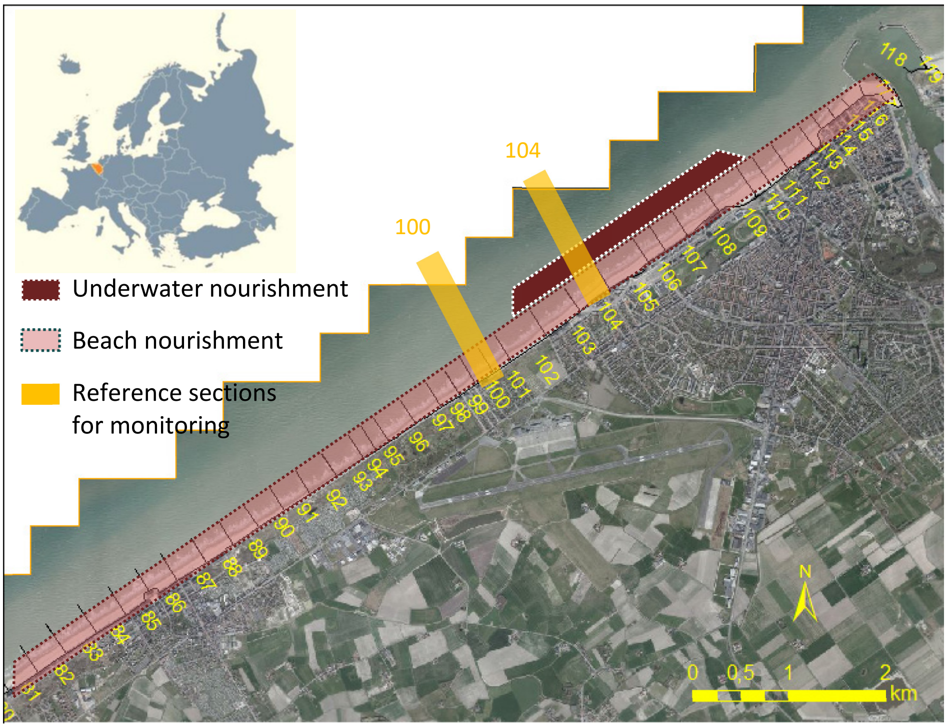


Figure 1 - Pilot site for shoreface nourishment test, Mariakerke coastal area and the reference sections.

The beach nourishment continues in the south-west direction up to section 77.

1.3 Mariakerke project site

The town center of Ostend is located side by side to the port. The historic town of Ostend was situated in the seafront where the sea dike is protruding 200m into the sea. In fact, it was held in place by coastal defenses throughout the 16th – 20th centuries, while the surrounding coast was allowed to erode and the coastline to retreat. In the beginning of the 2000’s, the coastal safety of Ostend center, where severe inundations had occurred in 1953, was evaluated by the Flemish coastal authorities to be the lowest at the Flemish coast with acute risk of overtopping and breaching of the existing old seawall. For public safety, an emergency beach nourishment was carried out in 2004. This fill was meant to raise the safety level immediately and awaiting the construction of a new western port dam in 2010, which will give rise to a naturally accreting coast (Bertels *et al.*, 2012).

Long jetties extend over more than 500 m distance from the coast in order to protect the entrance to the port (Figure 2) . The stretch of coast within a 5 km radius from Ostend is characterized by a sandy shore with visible cross-shore hard structures (groins), spaced 200 – 500 m alongshore. The greatest part of Ostend city develops west of the port jetties. The eastern part consists of a wide system of dunes that connects Ostend to De Haan. It is more natural, in the sense that no nourishments occur there.

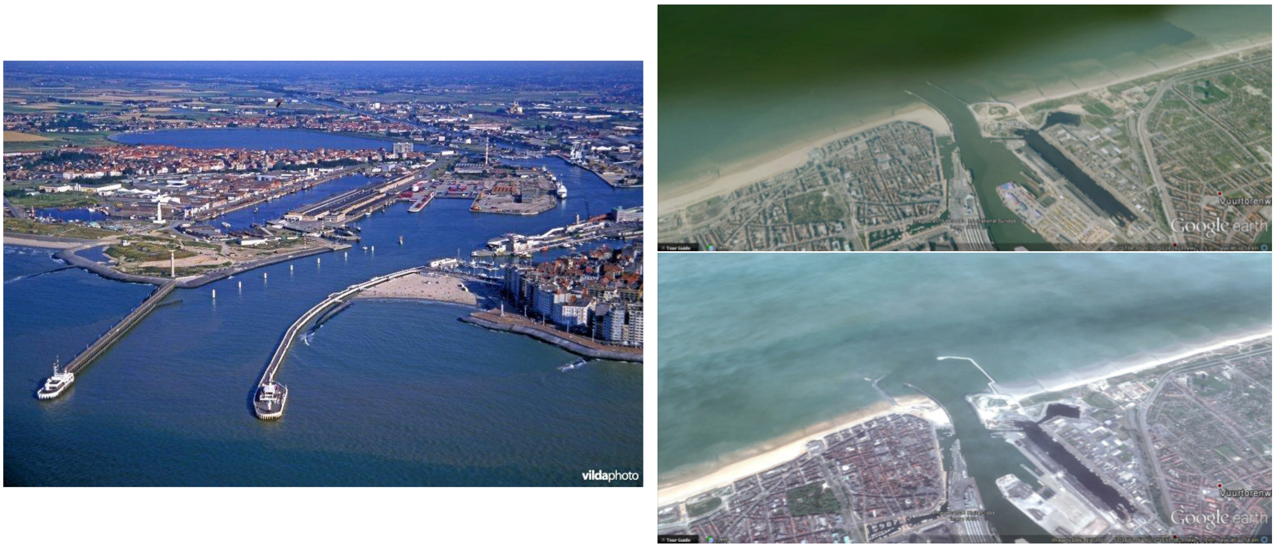


Figure 2 – Ostend port overview before 2004 (INSHORE, left), in 2007 (GoogleEarth, right top) and in 2011 (GoogleEarth, right bottom).

Before 2004, the beach in Ostend center consisted of a narrow strip in low tide and no beach at all at high tide. The emergency nourishment raised the beach profile, so that at high tide, a strip of about 200m of dry beach was created. The nourishment took place between April and June 2004. The median grain size before nourishment was about 0.2mm and after nourishment 0.3-0.35mm, locally up to 0.4mm (Bertels et al., 2012).

Mariakerke is a seaside village located west of the seaport, where yearly small-scale beach fills maintain a dry backshore berm in front of the seawall.

1.4 Structure of the report

The introductory chapter gives an overview of the project and an update in terms of completed analysis in the framework of the assignment. Chapter 2 gives a general overview of the available surveys and nourishments database, covering the timespan since the pilot nourishment. In Chapter 3 the morphological changes for the beach and the shoreface are evaluated based on these data. Sixteen boxes were define both in along- and cross-shore direction for a better description and quantification of the changes. Chapter 4 presents the volumetric calculations performed based on the changes presented in chapter 3. The changes in volume and the time trends in these changes are presented and discussed. Chapter 5 present the alongshore sediment transport at the study zone and variations of the shoreline position. Chapter 6 is dedicated to use of UNIBEST numerical model which was used to predict the evolution of the area in absence of human interventions and to estimate the wave height reduction due to the shoreface nourishment. In Chapter7 the main conclusions are formulated. Annexes I and II present details of the survey data processing.

2 Dataset and interventions

2.1 Survey data 2013-2018

Between 2013 and 2018, the shoreface and beach of the study area was frequently surveyed. Regular surveying of the emerged beach, between the dyke and the low water level (around 0 m TAW), was performed using airborne LIDAR (Light Detection And Ranging) technology. Normally, the surveys were conducted twice a year, once in spring and once in winter, except for 2014, when an additional survey was conducted after the pilot shoreface nourishment at Mariakerke. The high resolution datasets have approximately 1 m resolution. The nearshore bathymetry of study area has also been surveyed more or less twice a year, either with a single-beam bathymetric system or with a higher resolution multi-beam system (Figure 3). There was an additional survey conducted in July 2015, but the survey coverage was significantly different from the others. Its inclusion would cause a limitation of the areas of analysis so the survey carried out just one month before, in June 2015 was used in the analyses. In 2016 and 2017 only one survey per year was considered. The spatial resolution of the surveys is diverse, while with multi-beam technology it can be in the order of cm to 1m, using single-beam it can be in the order of 1 m cross-shore and of 100 m alongshore.

Three RTK-GPS cross-shore profiles have been carried out at each section 100 at Raversijde-East and section 104 at Mariakerke every month between September 2015 and December 2018 (Figure 3 and Figure 4).

The datasets are owned and kept at MDK Coastal Division and they are available in ASCII format (X, Y in Lambert 72 and Z in TAW[2]).

No sediment samples were collected during this project. However under the CREST project (final report under preparation), intensive sediment samples were collected in section 103 for 3 campaigns lasting around 10 days. In general, the sediment size was homogenous in alongshore direction ranging from 270 to < 300 µm for the upper beach. While sediment grain size gradually increased from the upper part to the lower part of the intertidal zone ranging from 300 to 390 µm. It is expected that sediment size is larger on the shoreface.

[2] The Belgian datum level (TAW, Tweede Algemene Waterpassing, Second General Leveling) corresponds with the lower low water at Oostende (1839–1858); 0m TAW is 2.0m below mean sea level; 0m TAW is 2.33 m below the zero of NAP (Datum Level of the Netherlands), which corresponds to average mean sea level during the last 300 years.

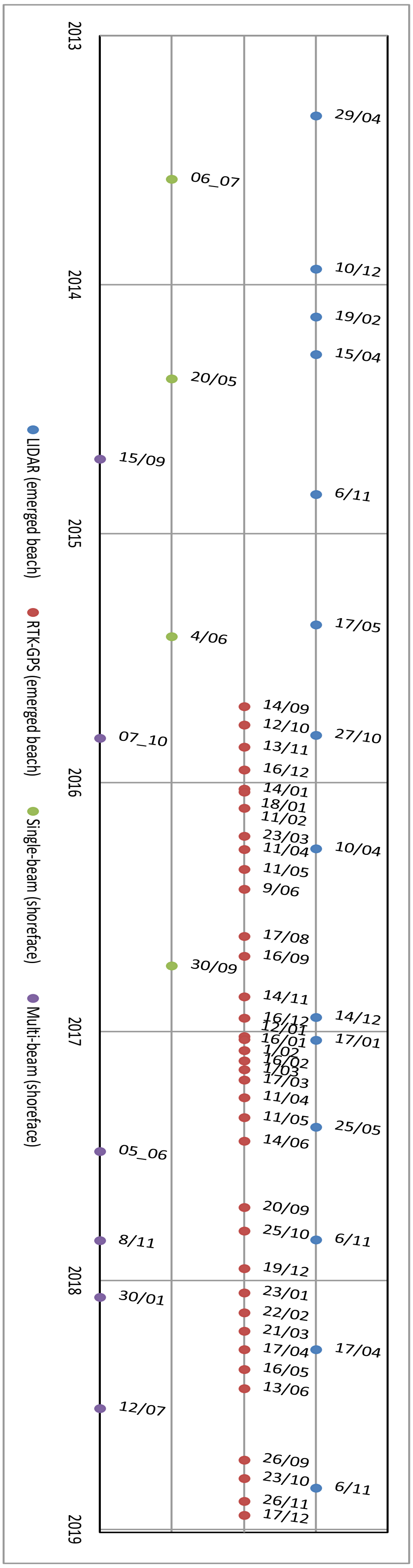


Figure 3 - Timeline of the topo-bathymetric surveys conducted at the study area between 2013 and 2018.

2.2 Nourishments 2013-2018

Table 1 presents in chronological order the dates of the beach surveys (light brown), the shoreface surveys (dark brown) and the dates and input volumes during the pilot nourishment. The sand volumes are measured on the ship before deployment.

Table 1. Topo-bathymetric surveys and sand volumes input to the study area between 2013 and 2017. For locations of the sections see Figure 1.

No.	Date	Sections	beach	shoreface
1.	29 April 2013	83-117	LiDAR survey	
2.	25, 26, 28 June - 02, 15 July 2013	83-117		single-beam survey
3.	10 December 2013	83-117	LiDAR survey	
4.	October2013 - February 2014	102-106	nourishment (681 200 m^3)	
5.		109-115	nourishment (822 200 m^3)	
6.	15 April 2014	86-117	LiDAR survey	
7.	15 April – 17 May 2014	102-108		nourishment (303 800 m^3)
8.	19 - 20 May 2014	83-105		single-beam survey
9.	22 April – 8 June 2014	74-89*	nourishment (968 800 m^3)	
10.	June 2014	97-102	nourishment (190 900 m^3)	
11.	15, 16, 18, 23 September - 2, 3 October 2014	91-116		multi-beam survey
12.	06 November 2014	90-116	LiDAR survey	
13.	2015	82-87*	nourishment (118 900 m^3)	
14.	17 May 2015	86-117	LiDAR survey	
15.	04, 05 June 2015	83-117		single-beam survey
16.	27 October 2015	83-117	LiDAR survey	
17.	30, 31 July, 3 - 31 August, 14 -29 September, 02 - 06 October 2015	91-114		multi-beam survey
18.	10 April 2016	86-117	LiDAR survey	
19.	13, 14 September 2016	83-117		single-beam survey
20.	14 December 2016	86-117	LiDAR survey	
21.	17 January 2017	83-117	LiDAR survey	
22.	02 May 2017	83-117		single-beam survey
23.	26 May 2017	83-117	LiDAR survey	

24.	06 November 2017	95-117	LiDAR survey	
25.	30 January 2018	98-109		single-beam survey
26.	5 February -4 March 2018	105-109	nourishment (315 381 m^3)	
27.	12 February - 23 March 2018	110-116	nourishment (424 631 m^3)	
28.	April 2018	90-117	LiDAR survey	
29.	July 2018	83-117		single-beam survey
30.	November 2018	90-117	LiDAR survey	

*not within the pilot site, but adjacent.

3 Morphological changes

The available datasets were used to analyse the morphological changes that occurred in the study area during the referred period and to estimate the volumes changes and trends.

3.1 Emerged Beach and Indicators

The available datasets were used to analyse the morphological changes that occurred in the study area during the referred period and to estimate the trend and evolution of the beach profiles.

3.2 Methodology

Three cross-shore profiles have been carried out at both section 100 at Raversijde-East and section 104 at Mariakerke every month between September 2015 and December 2018 (Figure 4).

Extra surveys were done before storm on 14/01/2016 and 12/01/2017; and after storm on 18/01/2016 (extended just until 110 m seaward) and 16/01/2017. Also the beach was surveyed twice in March 2017 but not in October 2016 and November 2017. However, no measurements were carried out during summer (from July to August) due to the touristic season. A RTK-GPS system was used in walking mode. The distance interval between profiles is around 150m and extend from the dyke to 300m toward the sea. The objectives of the monitoring profiles were to investigate the beach morphological change at a month basis and also to extract indicators. The divisions used to characterize the coastal system at the study zone are shown in Figure 7.

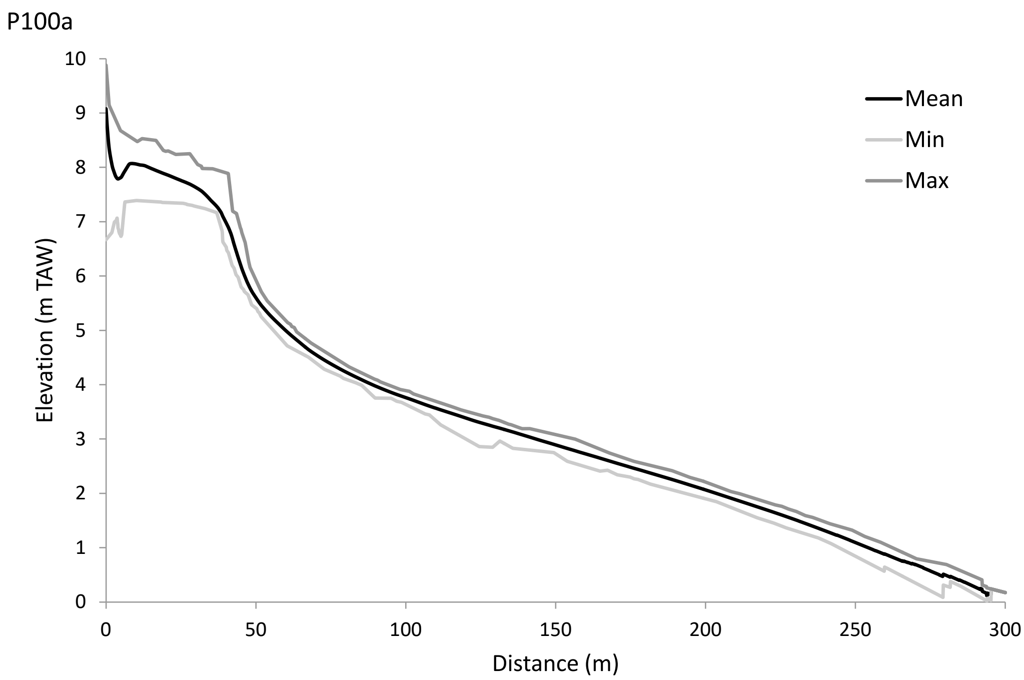
3.3 Emerged Beach and Indicators

3.3.1 Cross-shore profiles 2015-2018

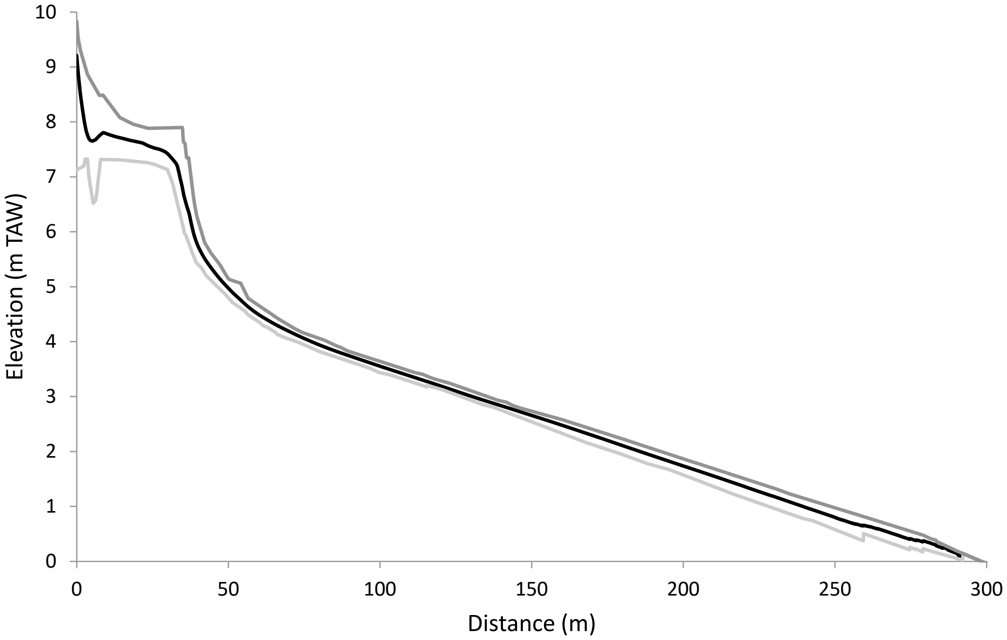
A shift (deviation from the straight line) up to 26 m was observed between cross-shore profiles located at the same position due to walking survey error (Figure 4). Therefore a correction was applied by re-projecting all the profiles using referenced profiles in ArcGIS. Then, the indicators such as intertidal width and slope of the intertidal beach and the dry beach were extracted from the re-projected, interpolated profiles. The references to calculate the intertidal beach width (intertidal beach slope are the MLWL and MHWL; and the MHWL and the sea dyke for the dry beach width (dry beach slope).

Figure 5 and Figure 6 show the envelope of the three re-projected cross-shore profiles for section 100 (a,b,c) at Raversijde-East and section 104 (a,b,c) at Mariakerke from September 2015 to December 2017 Both sections indicate the presence of a berm of the dry beach above +7.0 m TAW while the intertidal beach is with featureless and a gentle slope. The greatest elevation variability is found on the upper beach at a distance of less than 50 m from the dyke while the changes of the intertidal beach are usually minor (except for profile P104a and P104b). Thus, a spatial and temporal variability of the elevation is observed at a monthly scale.

Figure 4 – A) Map of the location of the cross-shore referenced profiles; B) Example of observed shift of a profile.



P100b



P100c

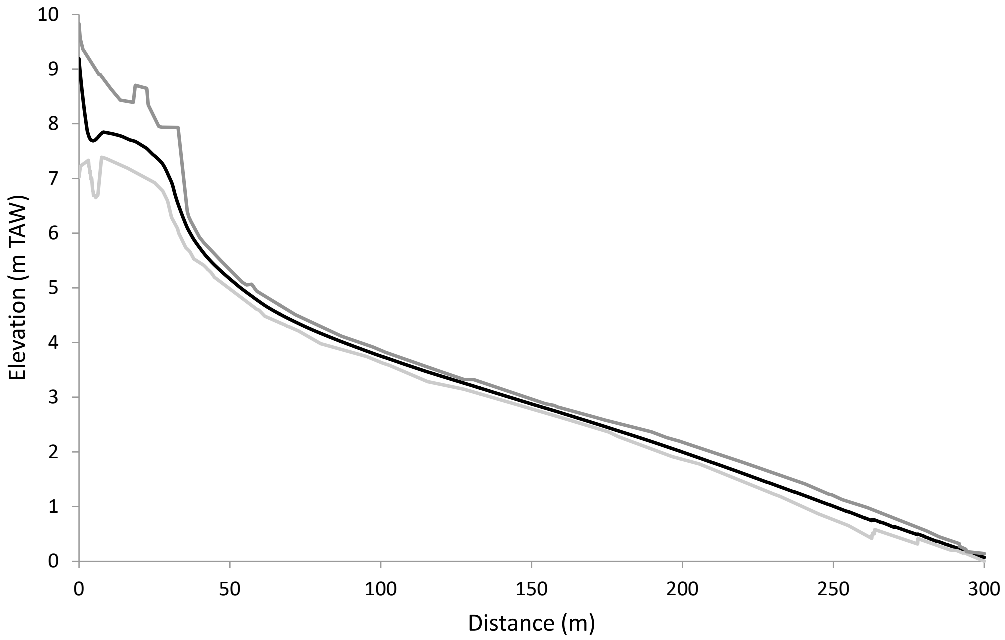
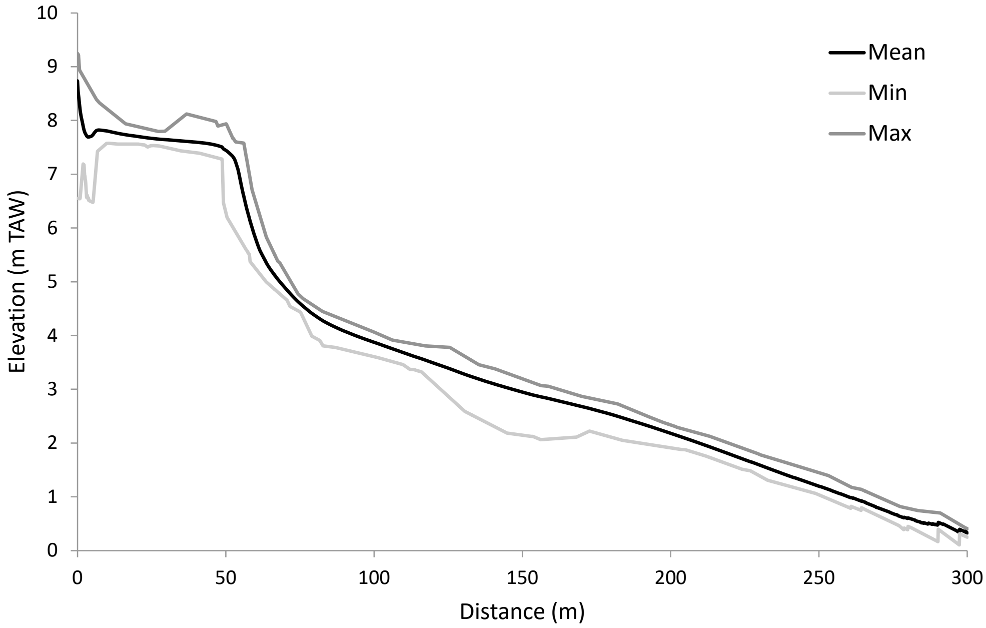
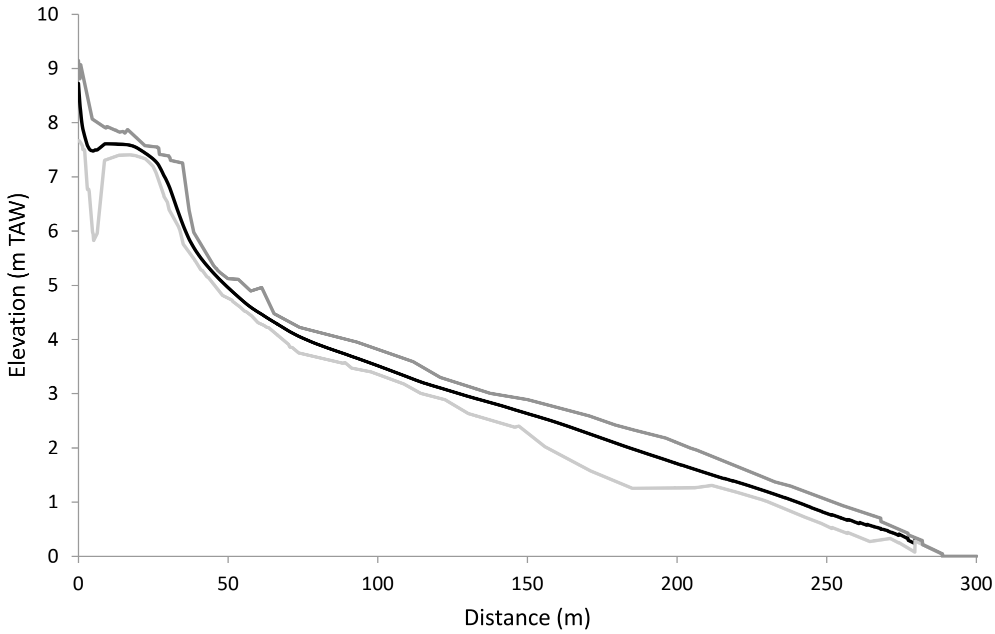


Figure 5 – Envelope of the cross-shore profiles for section P100 (a, b, c) at Raversijde-East from September 2015 to December 2017.

P104a



P104b



P104c

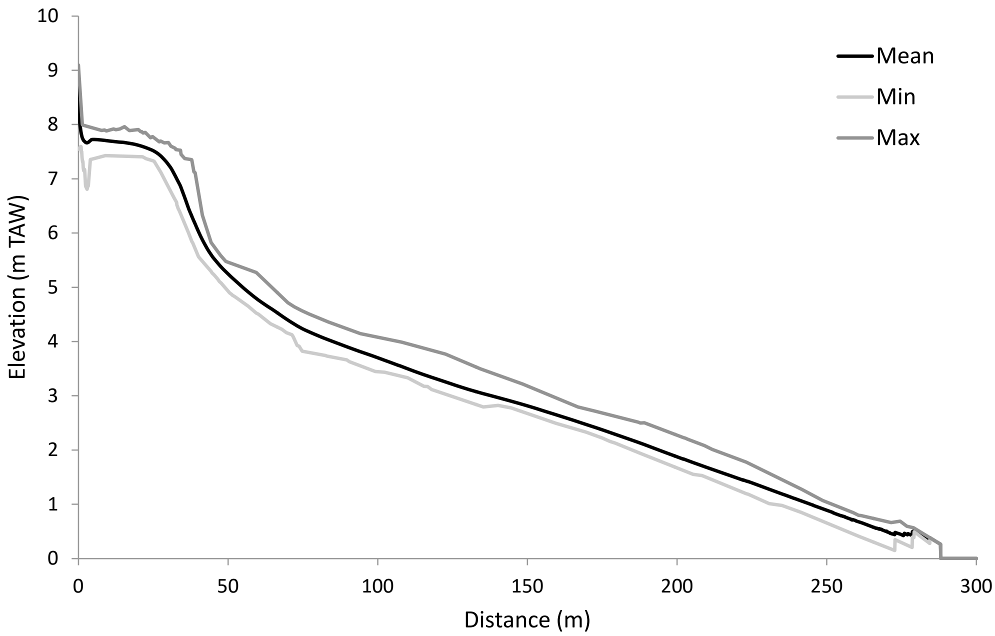


Figure 6 – Envelope of the cross-shore profiles for section P104 (a, b, c) at Mariakerke
from September 2015 to December 2017.

The width of the intertidal beach was estimated from the re-projected profiles interpolated with a distance of 0.10m at Raversijde-East (section 100) and Mariakerke (section 104). The assessment was made following the definitions of the morphological levels for the Mean High Water Level (+4.39 m) and Mean Low Water Level (+1.39 m) TAW. The intertidal beach width corresponds to the distance between MHWL and MLWL and the intertidal beach slope to the slope between these two levels. The width of the dry beach was also estimated from the re-projected profiles for both sections. It corresponds to the distance between the toe of the dyke (the point where the beach profile intersects the dyke) and the morphological level MHWL (+4.39 m). Figure 8 and Figure 9 present the indicators for the intertidal beach and dry beach for section 100 and 104 respectively.

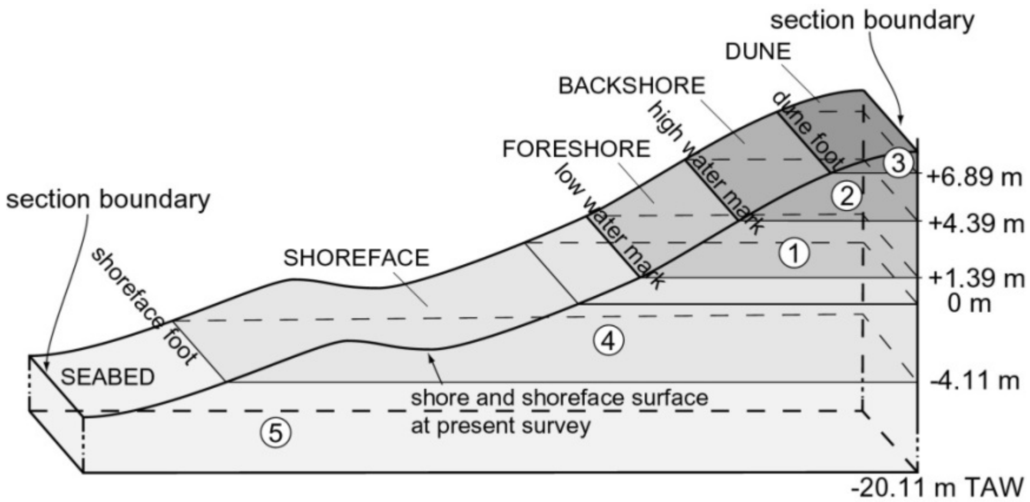


Figure 7 - Schematic representation of the cross-shore divisions at the Belgian coast (after Houthuys, 2012).

Intertidal beach width (beach slope)

A high spatial and temporal variability of the intertidal beach width is observed between profiles for both sections (Figure 3). The average of the intertidal beach width is 159 m from 2015 to 2018, and ranging from 169.8 to 148.6 m at section 100 at Raversijde-East. In general, the intertidal beach width for profile a and c were larger than profile b most probably due to the presence of the groins.

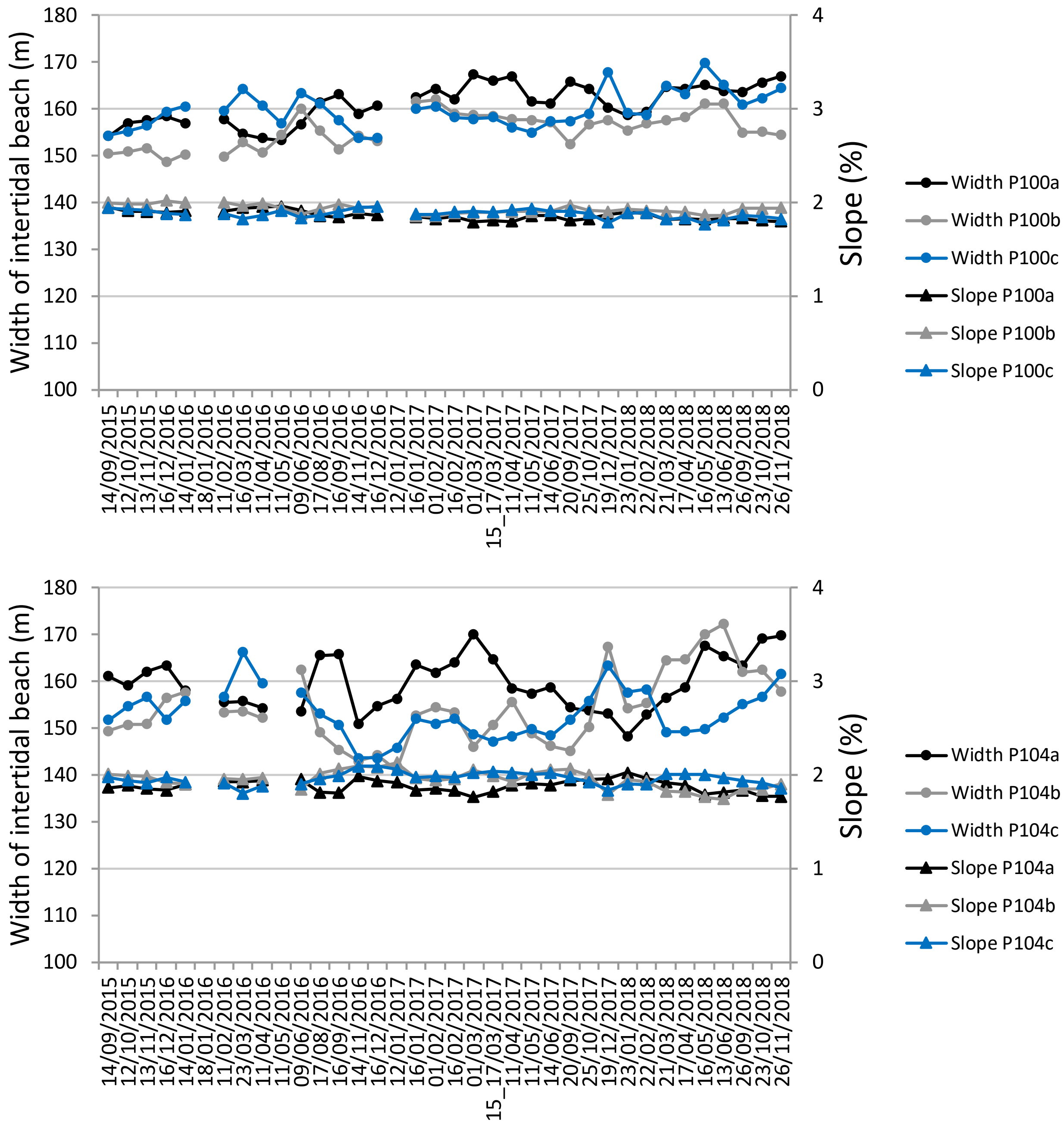
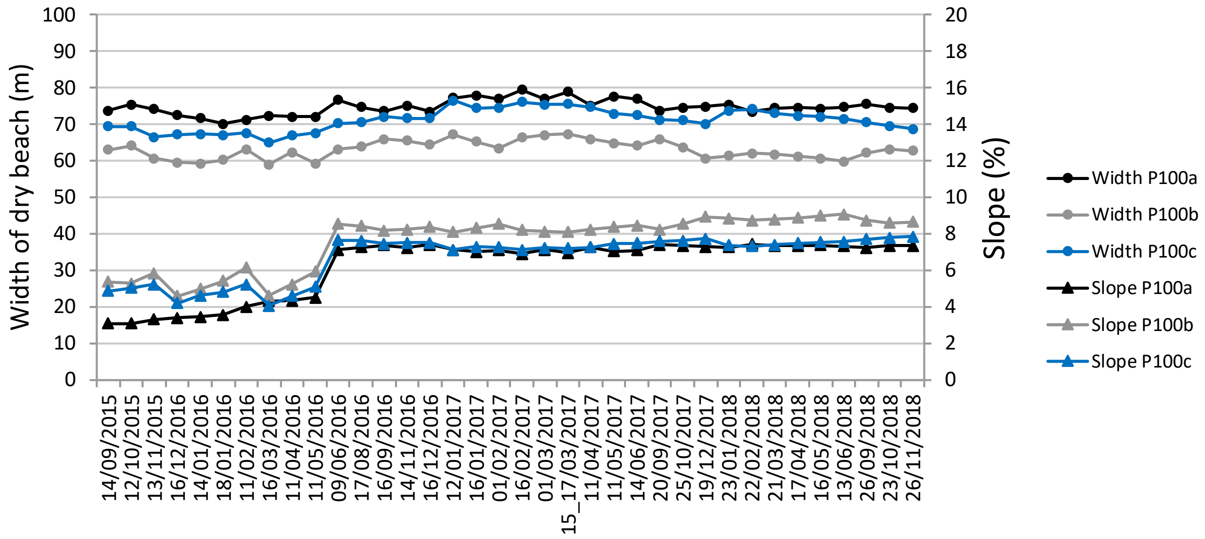


Figure 8 – Evolution of the intertidal beach width (slope) at Raversijde-East (section 100) and at Mariakerke (section 104).

The intertidal beach at section 104 in Mariakerke is characterized by a relative stable width (average 156 m and with a range from 144 to 170 m). However, a spatial variability between profiles occur with the largest width for profile a, followed by c and b except from March to September 2018. This is likely due to the presence of the groins which influence sediment deposition and erosion for the two extreme profiles of the section (a and c). The intertidal beach slopes are relatively stable ranging from 1.8 to 2.1% at Raversijde-East and Mariakerke. The monthly topographic monitoring started 19 months after the shoreface nourishment in October 2013 – February 2014 therefore it is difficult to observe any immediate effect of the nourishment in both sections. However, it can be noticed that there is a natural adjustment to maintain a certain slope of the intertidal beach below MHWL, probably as a reaction to the nourishments. Interestingly, the nourishment in section 105-109 carried in 2018 seems to have favorized an increase of the beach width in section 104 and in particular of the dry beach for profile 104c. This was probably due to the sand spreading during the nourishment.



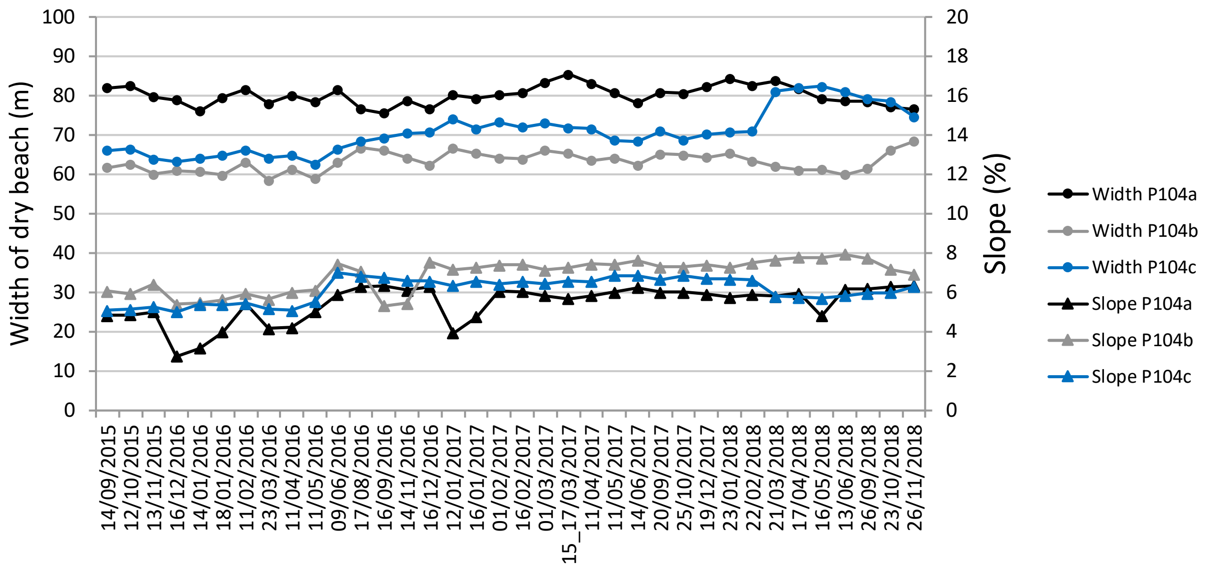


Figure 9 – Evolution of the dry beach width (slope) at Raversijde-East (section 100) and at Mariakerke (section 104).

Dry beach width

Figure 9 shows stability for the dry beach width for the three cross-shore profiles in the two sections at monthly scale. The width of the beach is the largest for profile a (average of 75 m for section 100 and 80 m for section 104). This is followed by the profiles c and b for both sections which are characterized by a width ranging from 59 to 76.5 m. Regarding the slope, defined as the gradient between the profile benchmark and MHWL, a gradual increase is observed and in particular for section 100 where the slope ranged from 3.1% in 2015 to 9% by the end of 2018. The most probable explanations lies in the rising of the beach level at the toe of the dyke. Also, the presence of a berm influences the slope indicator which was clearly the case in May and June 2016. In contrast, the slope of the dry beach was relatively stable in space and time for section 104 with an average of 6.1% and a standard deviation <1°.

Berms on the upper beach with a height above 7 m TAW and at a distance around 40 m from the dyke were always present. They were also characterized by a steep slope either driven by natural processes (storm) or human interference (bulldozers scraping beach). Under storm diving process, these berms could be referred as cliffs. Ridges of a few decameters high and above 4 m TAW were observed after some storms, last time in September and December 2019 and they were built by wave processes under energetic conditions.

3.4 Digital Elevation Models 2013-2018

The LIDAR datasets were processed using ArcGIS software (ArcMap 10.3.1) in order to get Digital Elevation Models (DEM's) with 1 m resolution. The processing methodology is explained in Appendix I and II.

To get insight into the changes of the active beach, the dry and intertidal beach and shoreface DEM's were combined to create an overall DEM of the coastal area.

To do this following steps were taken:

1) LIDAR DEMs below 1.2m TAW was usually visualized as noisy data due to the presence of the water reflection signal so that shoreface DEM was only considered. Above 1.2 m TAW DEMs were generated by giving priority to the LIDAR part there is no 'jump' at the seam between the two DEM's. The shallowest part of the bathymetric data is in fact also sometimes incorrect but further investigation needs to be carried out to define the specific error.
2) The shoreface DEM's, which have a grid size of 10 m were resampled to a resolution of 1 m, to make sure that no information from the LIDAR data (which has a resolution of 1 m) was lost when both DEM's where combined.
3) A Mosaic DEM was made by combining shoreface DEM and LIDAR DEM.

Because the LIDAR and multibeam soundings are not executed at the same time, a selection was made from the available datasets to become one combined dataset per year. To decide which datasets to use, an attempt was made to select two datasets with a sounding date as close together as possible, if at least the coverage of these soundings was extensive enough. For example for 2014 the LIDAR of April 15th was combined with the shoreface soundings of May and September (the sounding of September was used because the sounding of May didn't cover the whole area).

Furthermore, for 2013 the LIDAR of December 10th was used, combined with the shoreface sounding of June/July. There was also a LIDAR done in May, but this one was not selected because the LIDAR that was done just before the nourishment was preferred. Table 2 gives an overview of the soundings that were used.

After the creation of these rasters, the elevation differences between pairs of rasters were calculated. Due to the coverage differences existing between rasters and the aim of comparing the evolution of the two coastal areas where the pilot nourishment was constructed, four alongshore areas common to all the rasters were defined for analysis: the two coastal areas of the pilot site, Raversijde (coastal sections: 98-102) and Mariakerke (coastal sections: 103-105), and two extra coastal areas located respectively to the west (Middelkerke: coastal sections: 91-97) and the east (Ostend: coastal sections: 106-115) of the pilot area (Figure 10).

Table 2 – Overview of selected soundings for creation of combined DEM's.

Year	Beach data	Shoreface data
2013	10 December	25, 26, 28 June - 02, 15 July
2014	15 April	19 - 20 May 2014 and 15, 16, 18, 23 September - 2, 3 October
2015	17 May	4 – 5 June
2016	10 April	3 - 31 August and 13 – 14 September
2017	26 May	2 May
2018	April	July

In order to better understand the evolution of the nourishments, four cross-shore areas were defined, based on depth contours at -4,11 m TAW, +1,39 m TAW, 4,39 m TAW, 6,89 m TAW, based on the classification of Houthuys (2102).

The entire area is divided in 16 boxes for a detailed investigation of the sediment circulation after the nourishment were executed (Figure 10). The delimitations of the boxes follow isolines at the above mentioned elevation/depths using the pre-nourishment situation. The cross-shore delimitation is based on the cross-shore profile proposed by Houthuys (2012), but the dry beach and dune foot were merged for this case and their inland boundary is the first human made structure. The shoreface box is including most of the submerged active beach. A forth box, named sea floor was added to extend the study zone to a depth of -6.00 m TAW. This box covers an area just considered outside of the closure depth.

An ArcGis Tool was designed to assist in the evaluation of the raster changes by doing volume computations between the different rasters. As a first step, difference maps between pairs of rasters were calculated using Raster Calculator in ArcGIS. Next, Surface volume was used to compute the volume differences for a list of polygons (the aforementioned boxes). The volume above and below zero was calculated, using the difference rasters, as to determine the eroded and deposited volume. The net volume difference was calculated by subtracting the eroded volume from the deposited volume.

These calculations were done for every combination of the created yearly DEM's.

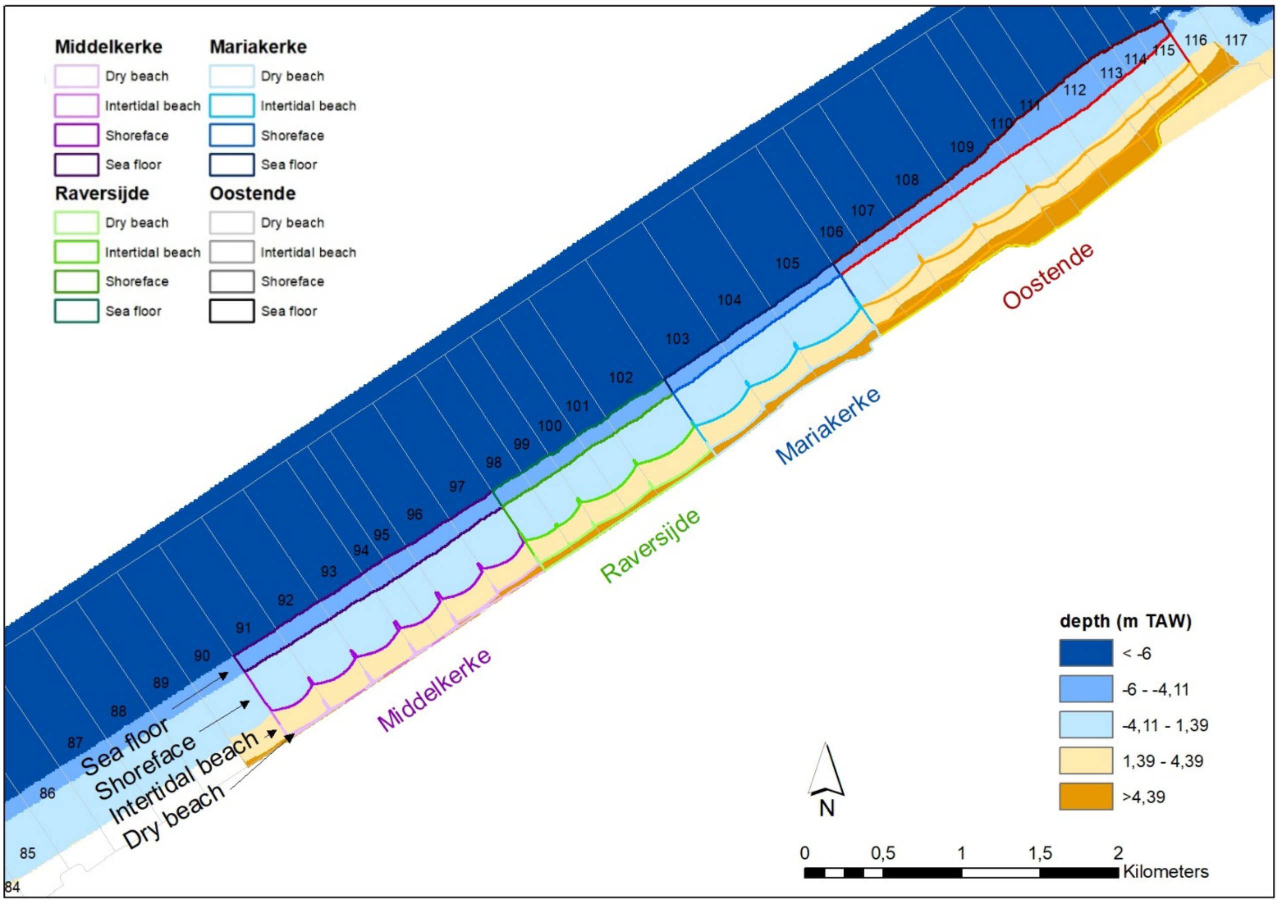


Figure 10 – Delineation of alongshore and cross-shore research boxes.

3.5 Volume difference maps

The investigation of the volume changes for the area subject of the nourishment experiment was performed both qualitatively and quantitatively.

To follow the morphological changes before and after the nourishment 12 volume differences maps were built. In Table 3 all DEM comparisons carried out to analyse the volume differences are listed. The differences between the situation pre-nourishment (2013) and the years 2014 to 2018 were done in order to assess the evolution of the study zone in general. The differences between the situation post-nourishment (2014) and the years 2015 to 2018 were done to explain the evolution of the nourishment. The differences between consecutive years were carried out to observe eventual sudden changes in the erosion/deposition pattern which might have occurred.

The difference maps are a useful method to quantify the sand circulation within the active beach. All the volume difference maps are shown in Figure 12 to Figure 23 and the 16 boxes division is also shown in every map.

Table 3 – Type of comparison between DEMs carried out during the project.

Type of comparisons	Volume differences				
Pre-nourishment	2014-2013 Figure 12	2015-2013 Figure 13	2016-2013 Figure 14	2017-2013 Figure 15	2018-2013 Figure 16
Post-nourishment	2015-2014 Figure 17	2016-2014 Figure 18	2017-2014 Figure 19	2018-2014 Figure 20	
Consecutive years	2016-2015 Figure 21	2017-2016 Figure 22	2018-2017 Figure 23		

A summary of the evolution of the beach at the study zone is presented in Figure 11. The post-construction nourishment evolution is shown in Figure 11C where comparison between 2014 and 2017 digital elevation models was performed. The trends for the local sand circulation are more visible than in the previous comparison. As expected, sand from the shoreface is eroded for both areas subject of the experiment, Raversijde and Mariakerke, and, most probably, large parts of this sand is deposited on the shoreface of the Ostend sector. However, at Mariakerke, the sand deployed on the shoreface is reorganized into a submerged bar. The sand deposited on the intertidal beach is eroding. Apart from alongshore redistribution this material is in cross-shore migrating into two distinct directions: 1) to the dry beach, by aeolian transport as a main driving force, but also due to the local human interventions and 2) to the shoreface.

One particular finding is a correction of the local closure depth at yearly scale when the evolution of the sea floor sector is investigated. This value was estimated on a decadal scale at -4.11 m TAW by Houthuys (2012) and calculated at -5.25 m TAW by Vandebroek et al. (2017). When digital elevation models are compared for a period of approximately 5 years it is clearly visible that the circulation of the sand can be considered insignificant at the depth of -6.00 m TAW, the offshore limit of the study zone.

The monitoring period extends from 2013 to 2018 and the bathymetric and topographic data were combined every year to produce one digital elevation model. However, in 2018 a beach and shoreface nourishment was performed in the study area and it is clearly visible in Figure 23. A volume of 0.74 million m^3 of sand was deployed between profiles 105 and 116, partially covering the Mariakerke box and totally covering the Ostend box. Therefore, analysis of the nourishments evolution realized in 2013 – 2014 will be only discussed until 2017. Even for this time period the study zone evolution was significantly influenced by the beach nourishments performed in the immediate vicinity, at the south-western boundary, in 2014 and 2015 and with a cumulated volume of 1.16 million m^3 of sand (Table 1).

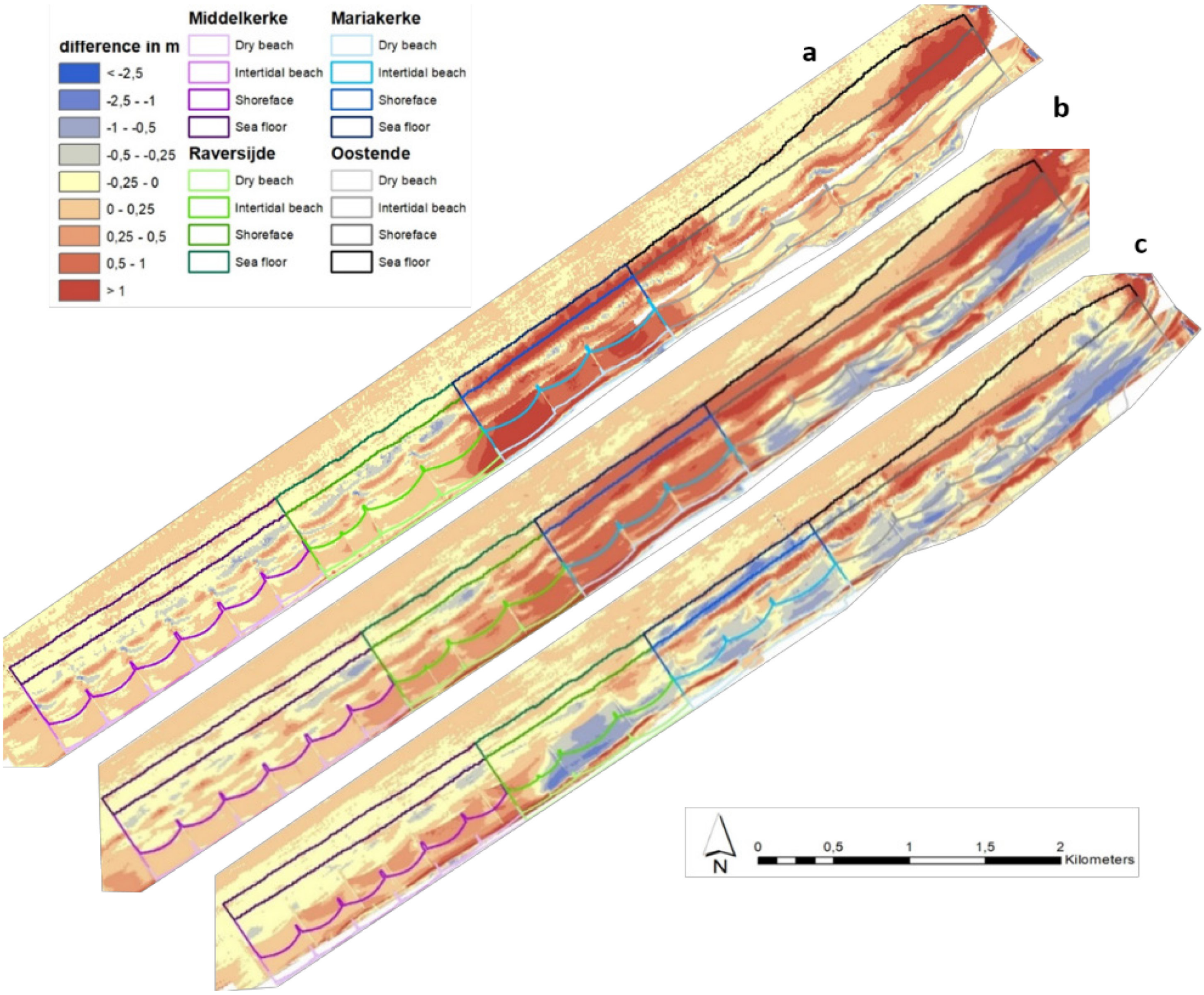


Figure 11 - The digital elevation model difference between different years: a) difference between 2014 and 2013; b) difference between 2013 and 2017; c) difference between 2014 and 2017.

<u>Evolution of the study area with the reference the 2013 pre-nourishment situation</u>

Figure 12 show the volume differences between the pre-nourishment and situations, except for the Raversijde nourishment (no. 10 in Table 1). Beach and shoreface nourishments at Mariakerke (no. 4 and 7) as well as the nourishment at Ostend (no. 5 in Table 1) are clearly visible. The last mentioned nourishment was performed both on the beach and shoreface, but the proportion between the two is not precisely known, so it was assumed to be divided in equal parts. However, the beach nourishment executed at Raversijde is not visible since it was performed after the seasonal topographic survey.

Along with the expected accumulations visible in Figure 12 due to the nourishments, some erosion areas can be observed especially at the middle depths on the shoreface area at Mariakerke and both at the shoreface and beach at Ostend area. The surveys used to construct the 2014 DEM (no. 6 and 8 in Table 1) were carried out 2 – 3 months after the nourishments, therefore the erosion spots indicate the incipient re-organisation of the deployed sand into the active equilibrium of the beach. This is confirmed by the comparison with the surveys carried out in 2015 (Figure 13). In this comparison the beach survey carried out at Raversijde is visible and the sand accumulation is less than at Mariakerke beach. In Figure 14 (2016 – 2013) the re-organisation of the deployed sand is continuing through formation and shore migration of a large bar at the Mariakerke shoreface, faster alongshore circulation of the sand deployed on the shoreface and erosion of the intertidal beach at Ostend. The later one could also have human induced causes since intense beach preparation for the touristic seasons was observed.

In Figure 15 (difference between 2017 and 2013) the sand circulation follows the same trends, but for at Middelkerke – Raversijde areas a sand bar on the shoreface is formed and migrates towards the shore. The erosion areas at Ostende appear larger than the previous year. The comparison pre-nourishment situation in 2013 to year 2018 (Figure 16) show accumulation almost in the entire study zone due to large nourishment carried out during this year (no. 26 and 27, Table 1) on both beach and shoreface in the area Mariakerke – Ostend. Only a limited part of the intertidal beach next to the Ostend port and outside of the sediment budget box still display loss of volume and this is due to human activities related to beach preparation for touristic season.

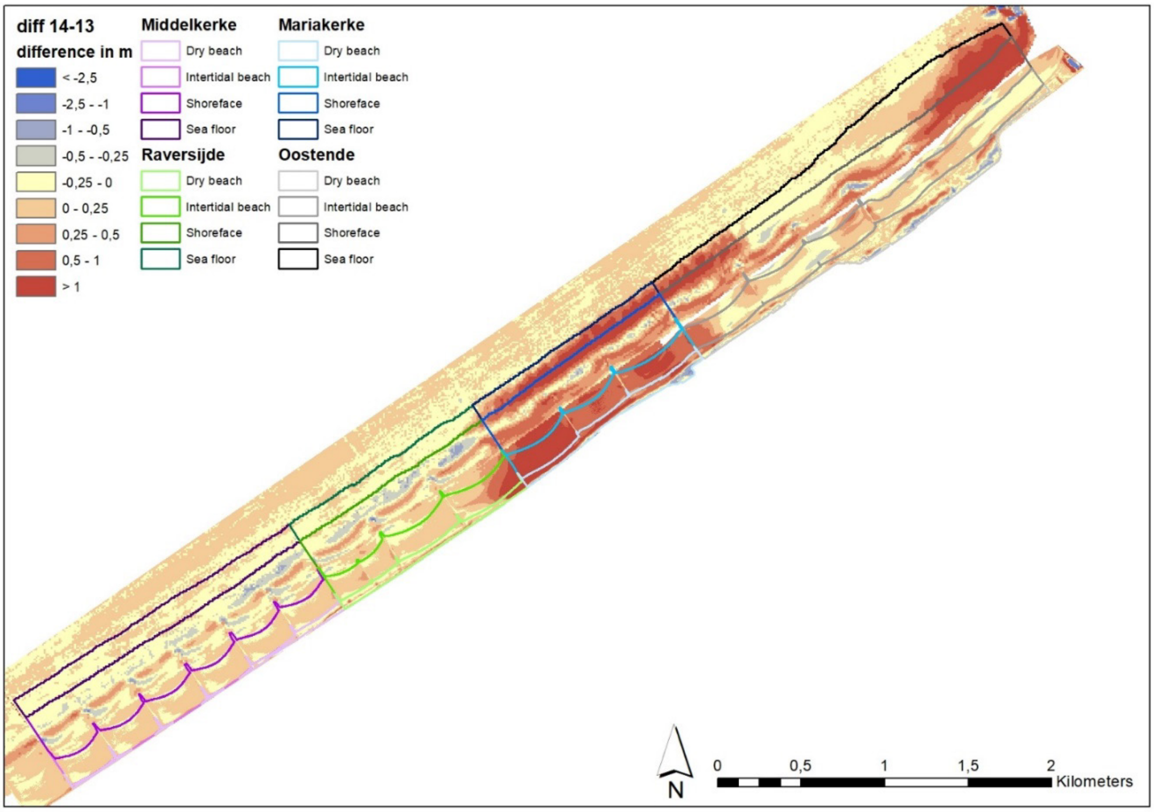


Figure 12 – Volume difference between 2014 and 2013.

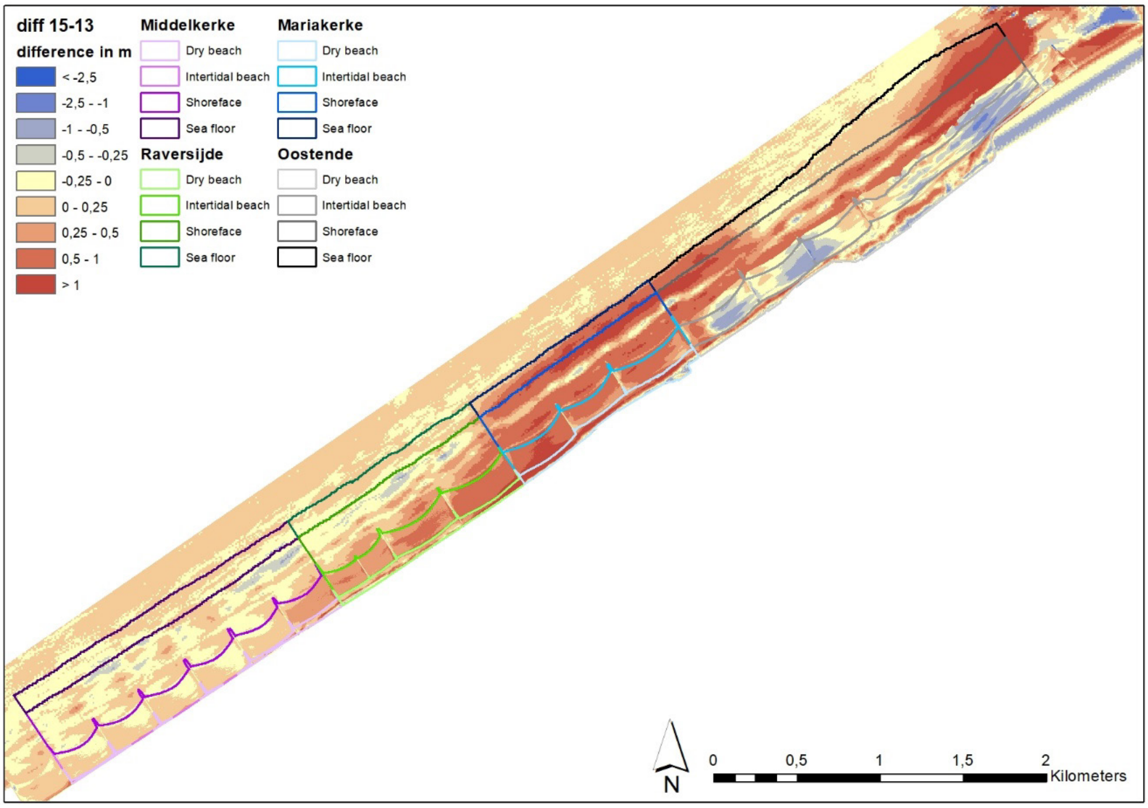


Figure 13 – Volume difference between 2015 and 2013.

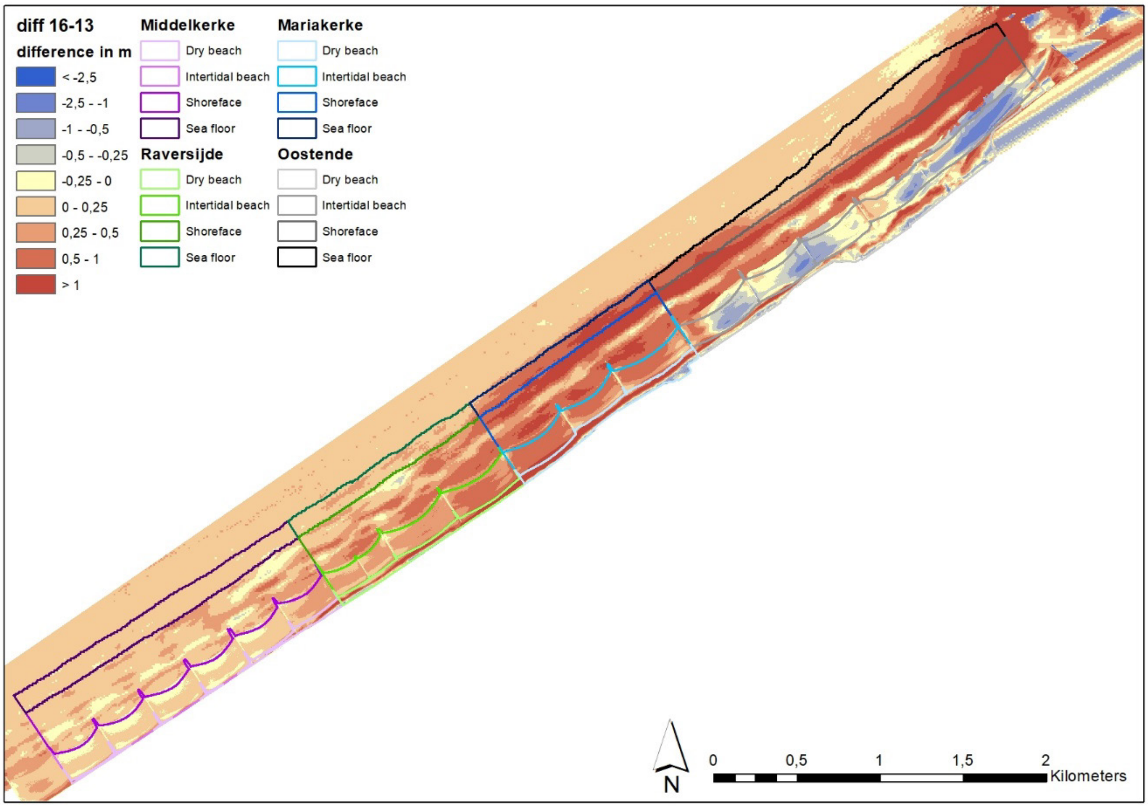


Figure 14 – Volume difference between 2016 and 2013.

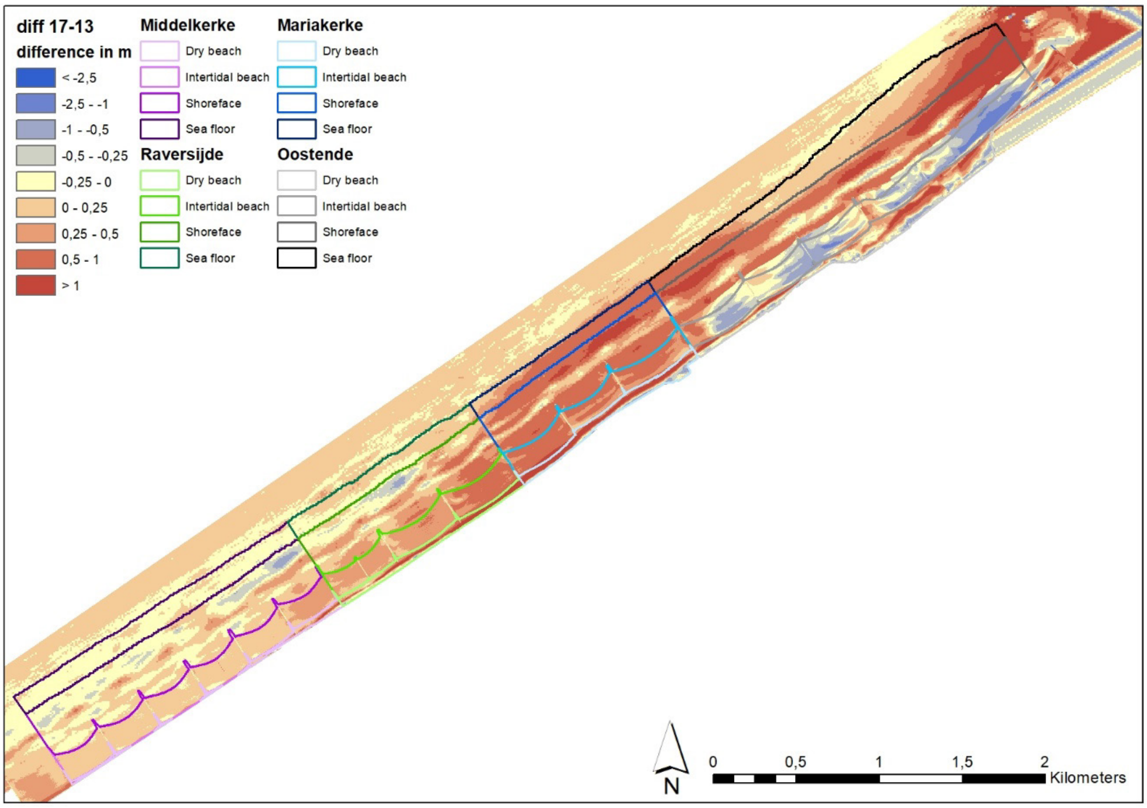


Figure 15 – Volume difference between 2017 and 2013.

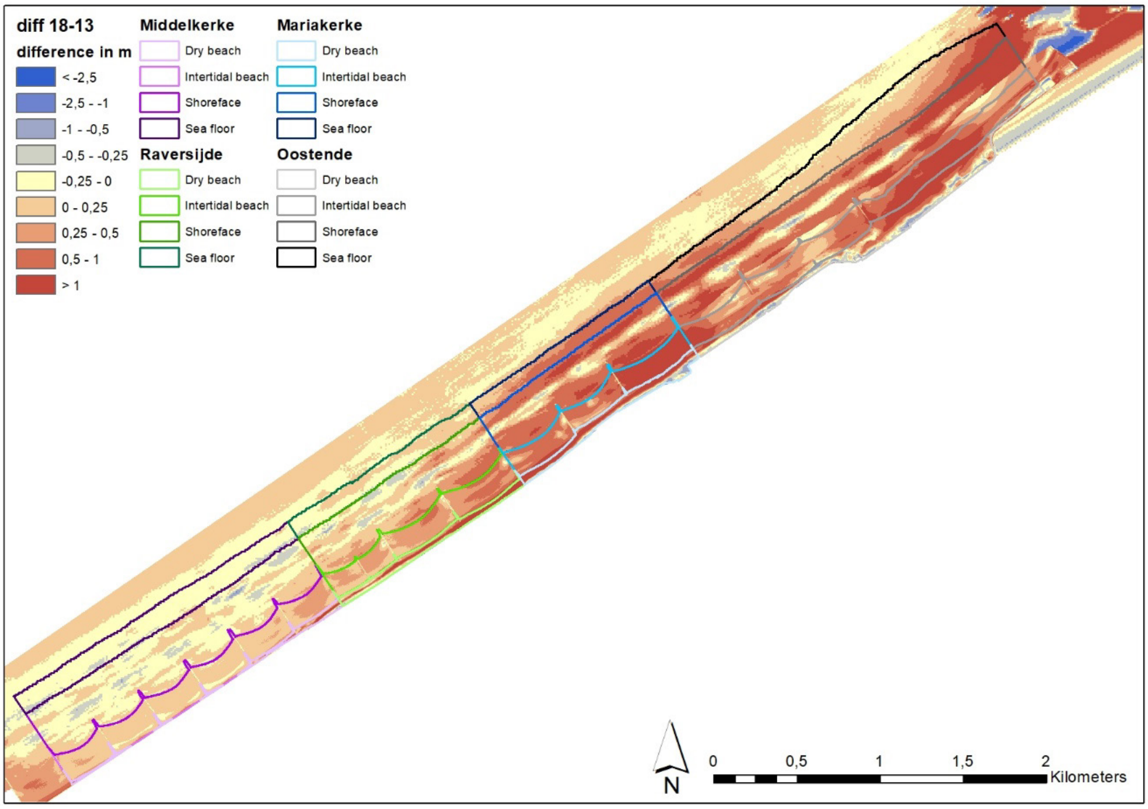


Figure 16 – Volume difference between 2018 and 2013.

Evolution of the study area with the reference the 2014 post-nourishment situation

The beach volume comparisons having as reference the first surveys after the main surveys were carried out show the same trends as for the comparison with the pre-nourishment situation. However, these trends are easier to observe since the volumes are smaller. A clear trend is visible at intertidal beach (Figure 17) where the nourished sand rapidly moved to the dry beach and to the shoreface. Formation of two sand bars and migration towards inland are also visible at Mariakerke and Ostend, due to the fast re-organisation of the nourished sand. At Mariakerke the formation of a trough is visible around the -5.00 m TAW depth and it formed as a consequence of the sand bars migration. Two years after the nourishment the sand bars at shoreface are still in place at Mariakerke, but at Ostend sector the two sand bars tend to merge into just one bar (Figure 18).

In 2017, there is just one sand bar at both Mariakerke and Ostend on the shoreface, significant volumes of sand moved from the intertidal beach and upper shoreface to the dry beach (significant growth) and to the lower shoreface. Similar situation can be observed at Raversijde, but less at Middelkerke (Figure 19).

The large nourishment carried out at Ostend in 2018 (no. 26 and 27, Table 1) interfere with the evolution of the initial nourishments. However, on the other three sectors, the evolution follow similar trends with previous three years (Figure 20).

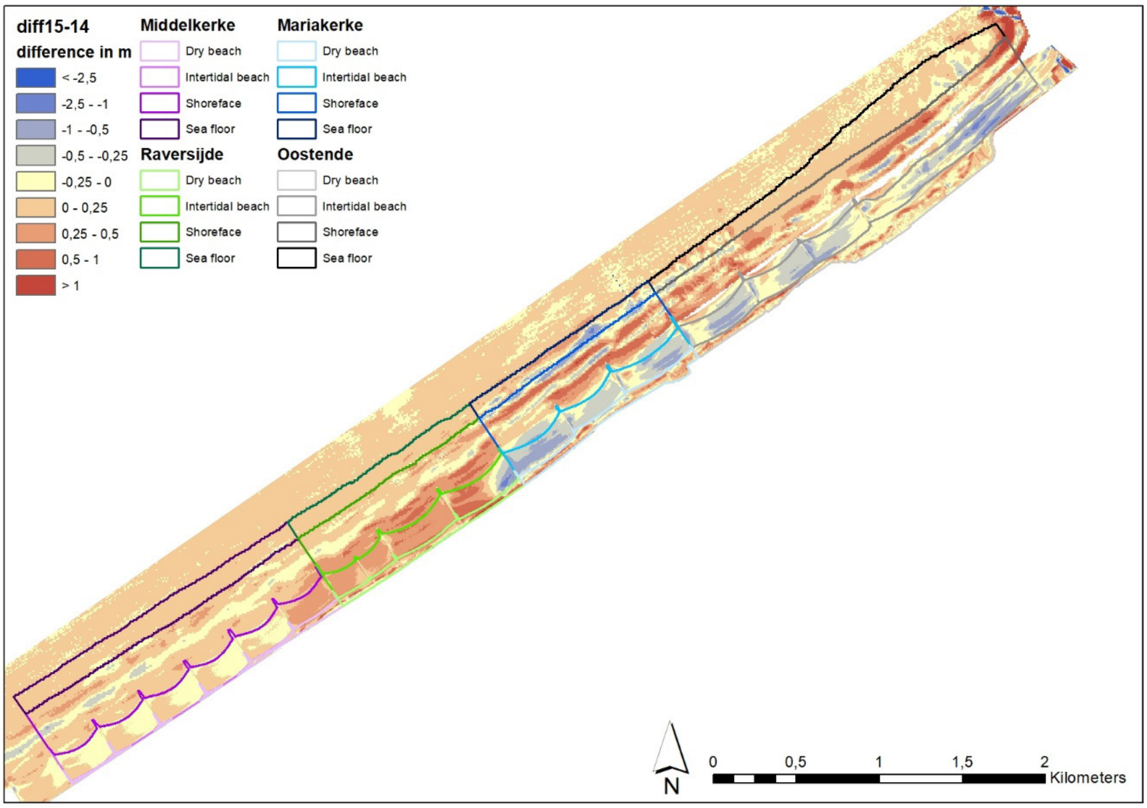


Figure 17 - Volume difference between 2015 and 2014.

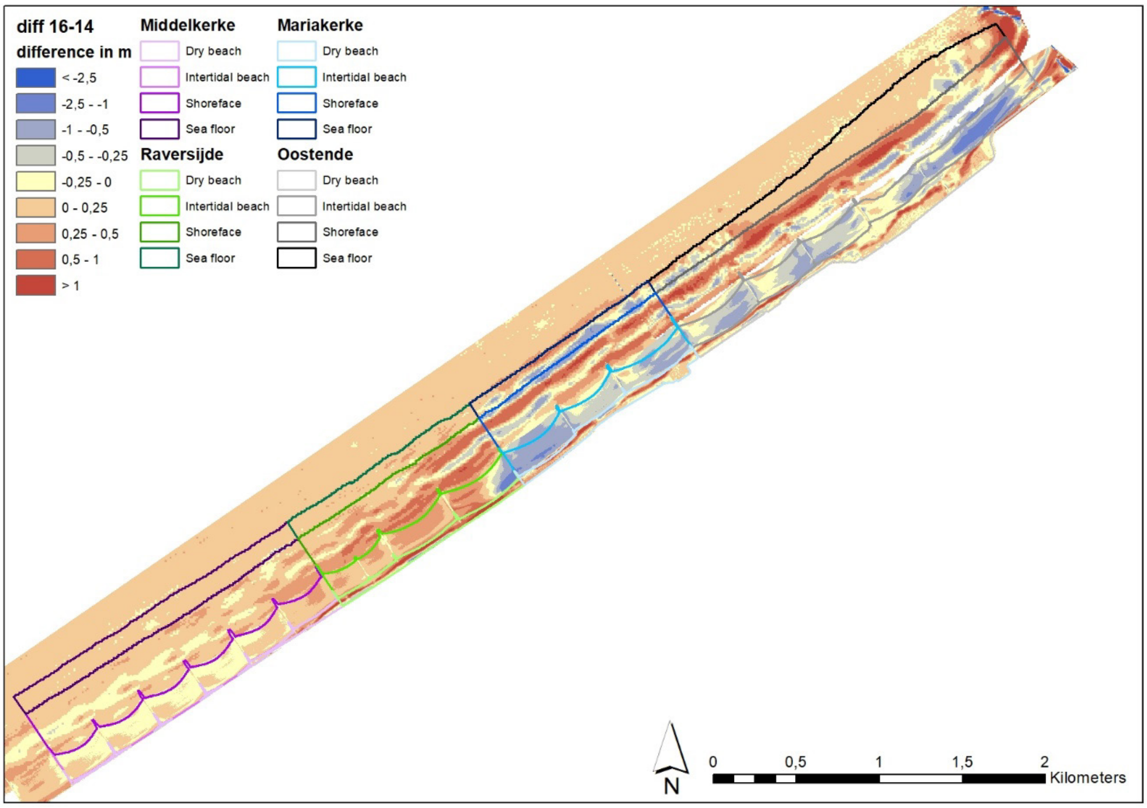


Figure 18 - Volume difference between 2016 and 2014.

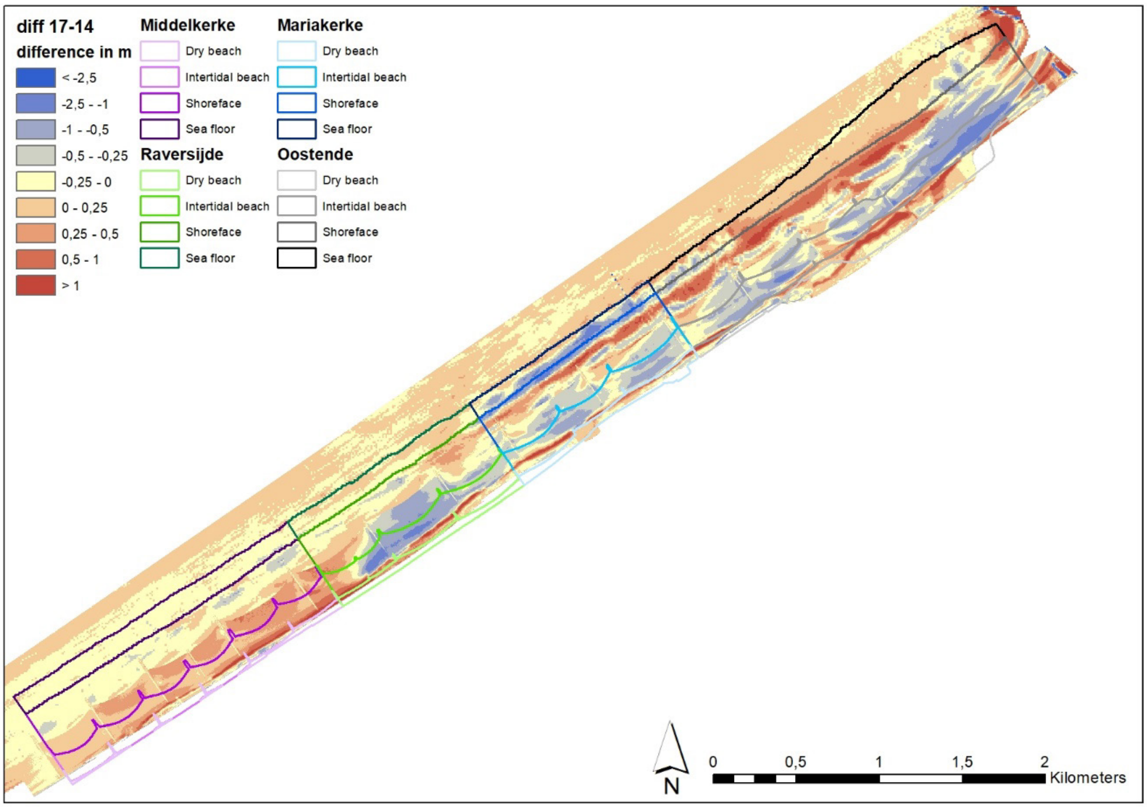


Figure 19 - Volume difference between 2017 and 2014.

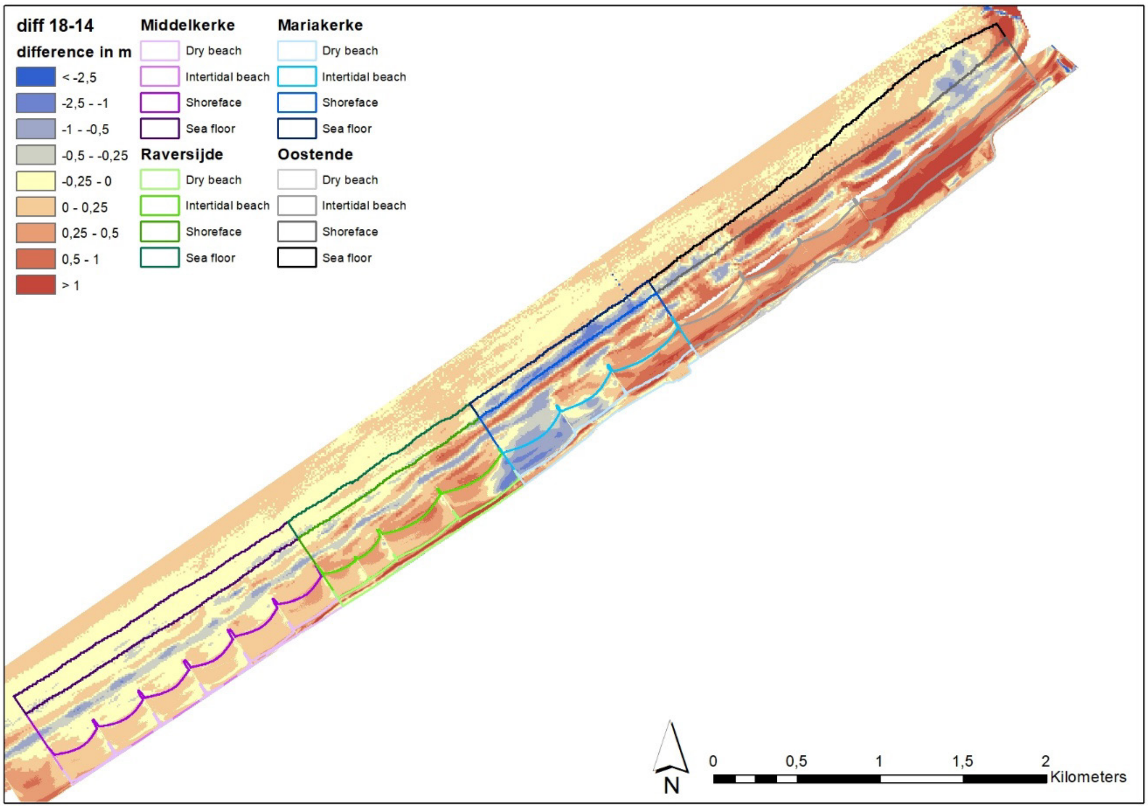


Figure 20 - Volume difference between 2018 and 2014.

Evolution of the study area between consecutive years

In Figure 21 evolution between 2015 and 2016 is shown. The formation of the sand bar at lower shoreface is clearly visible for most of Mariakerke and Osted boxes and less visible for boxes Middelkerke and Raversijde, with formation of a trough at the upper shoreface just for boxes Marikerke and Ostend. Erosion of the intertidal beach is visible for these two boxes. In Figure 22 (2017- 2016) the trough is positioned at the lower shoreface clearly indicating migration of the submerged sand bars. The intertidal areas seem to generally gain sand, except for the Ostend box where some erosion areas alternates with accumulation areas. These paterns at Ostend occur probably due to human interventions. The comparison between 2017 and 2018 (Figure 23) is dominated by the new large nourishment. However, some trends are still visible: at Middlekerke and Raversijde the trough and sand bar switched their position indicating offshore retreat of the sand bar, while the rest of the beach is stabile. For Mariakerke and Ostend the largest trough is positioned between the two submerged sand bars.

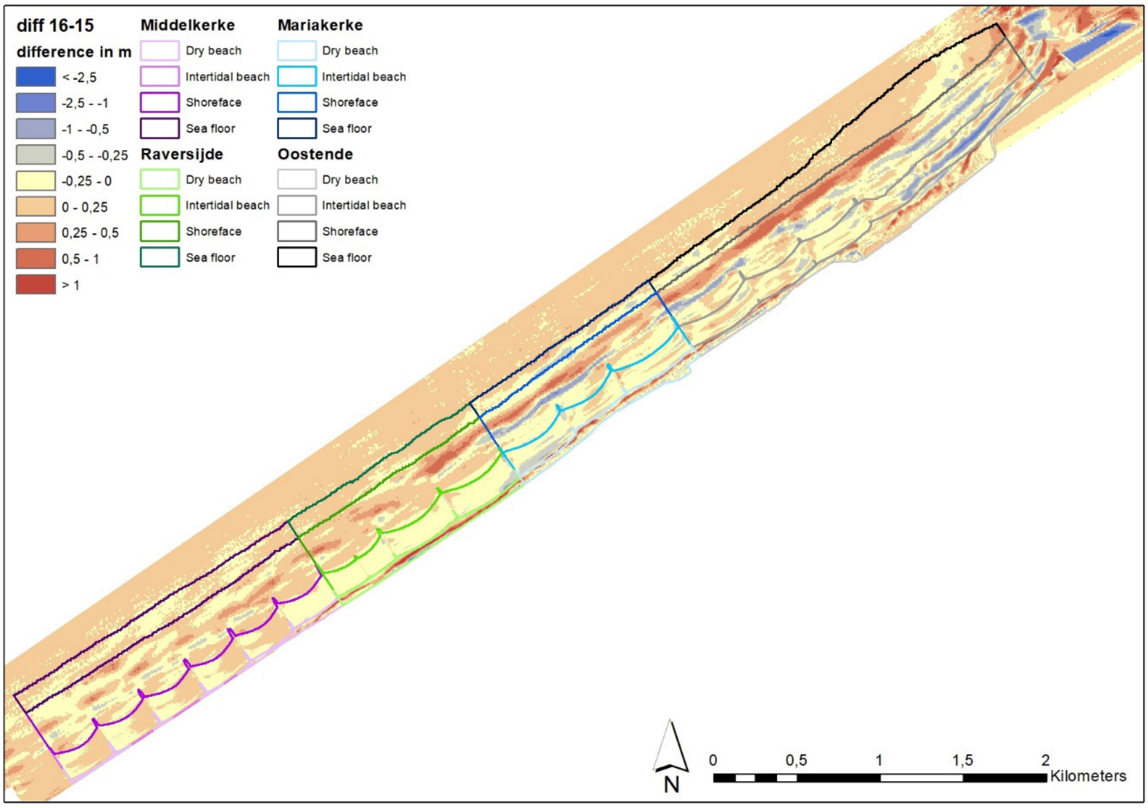


Figure 21- Volume difference between 2016 and 2015.

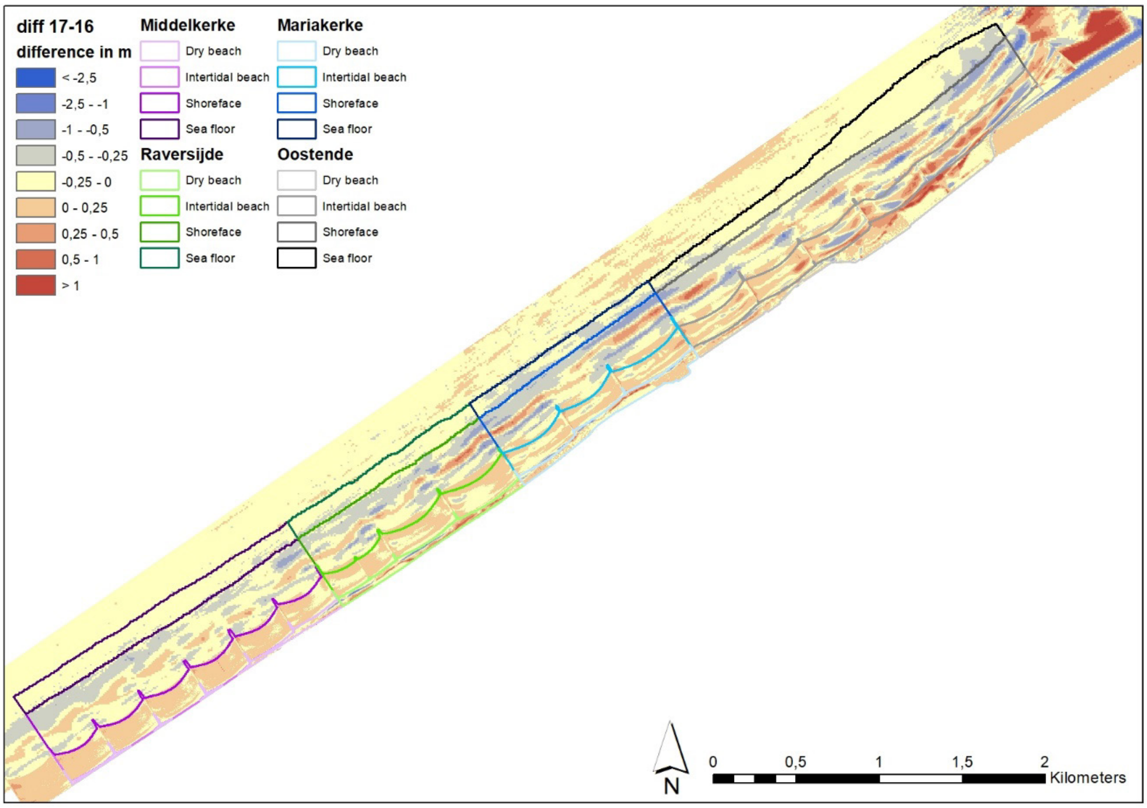


Figure 22 - Volume difference between 2017 and 2016.

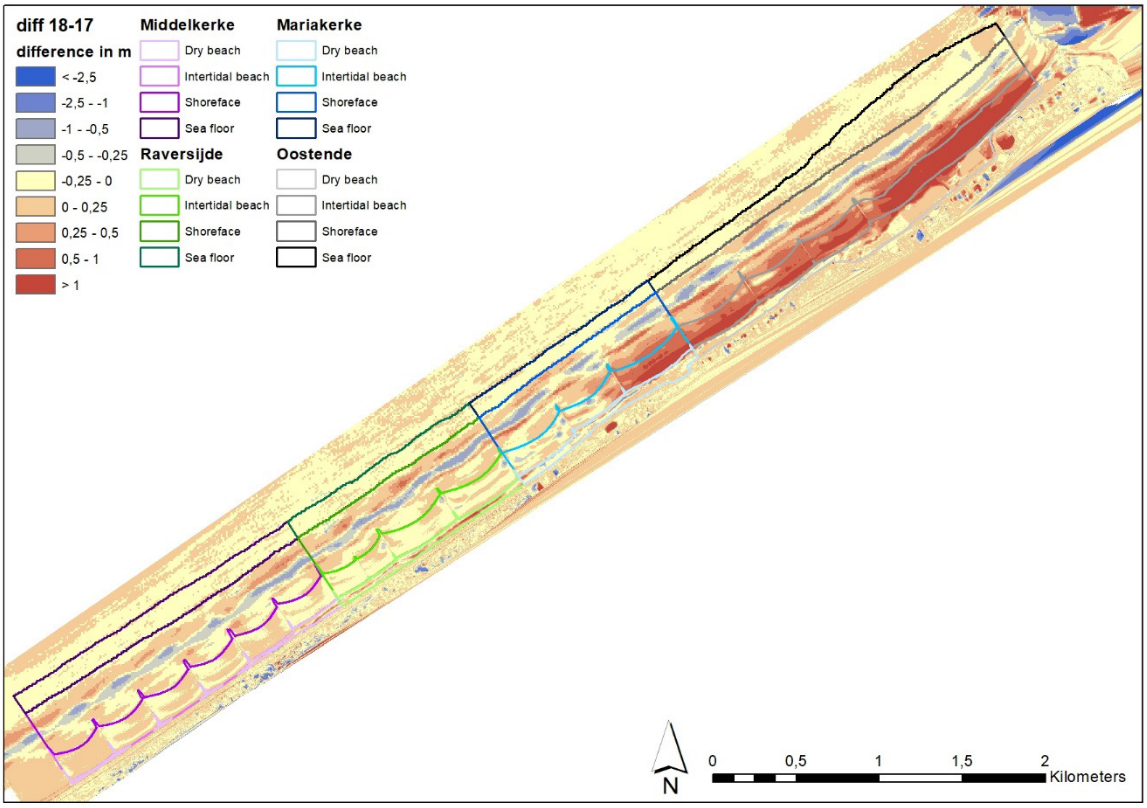


Figure 23. Volume difference between 2018 and 2017.

4 Volume calculations

Evolution of the sand volumes in the study area in terms of absolute and normalized values are presented in this chapter. The performed nourishment as listed in Table 1 took place during 2013 and first half of 2014.

4.1 Absolute volumes

The dynamics of the nourished volumes is significant and keeps constant trends. In Table 4 a detailed situation of the absolute volumes is presented and the warm colours show deposition, while the cold colours indicate erosion. The normalized situation is presented in Table 5. The analysis of the volumes reflects the trends observed in the sub-chapter 3.5 while quantifying the changes for each along and cross-shore beach unit.

In Table 6 the efficiency of the nourishments is presented by calculating the remaining sand in each of the four areas every year: Middelkerke, Raversijde, Mariakerke and Ostend; from the dyke until the -6 m TAW depth contour. As sometimes the nourishment locations do not exactly coincide with the defined areas a new calculation was made and every nourishment was divided proportionally to each box area.

Table 4 – Volume differences matrix between all surveyed years and all along- and cross-shore divisions (in m^3) in absolute values.

		14-13	15-13	16-13	17-13	18-13	15-14	16-14	17-14	18-14	16-15	17-15	18-15	17-16	18-17
Middelkerke	Dry beach	2 112	6 266	8 758	8 400	11 183	4 097	6 647	6 279	9 090	2 425	2 179	4 998	-1 229	2 798
	Intertidal	16 196	24 831	22 266	39 460	43 806	8 587	7 275	23 321	27 606	-4 238	14 745	17 268	14 018	4 277
	Shoreface	12 400	5 127	56 102	7 692	-8 270	-7 091	43 905	-4 477	-20 453	47 528	2 746	-16 437	-54 143	-15 920
	Sea floor	-871	1 801	13 903	-8 832	-22 842	2 782	14 831	-7 860	-21 858	10 855	-10 526	-25 732	-24 609	-13 883
Raversijde	Dry beach	11 548	30 017	46 361	50 539	50 263	18 448	34 812	38 960	42 913	15 320	18 262	23 951	2 104	4 597
	Intertidal	48 115	103 683	77 757	85 057	62 267	55 597	29 632	37 009	27 294	-27 130	-20 889	-29 487	4 988	-9 681
	Shoreface	11 330	51 941	107 542	77 915	84 033	40 664	96 279	66 721	59 593	53 498	24 489	16 948	-33 429	-7 171
	Sea floor	1 047	7 567	20 226	10 524	9 380	6 567	19 273	9 549	4 379	11 915	2 529	-2 805	-10 974	-5 012
Mariakerke	Dry beach	49 752	58 927	66 450	68 763	67 932	9 376	16 692	18 619	18 153	6 753	7 670	8 009	380	-444
	Intertidal	191 373	125 610	106 379	110 497	168 292	-65 795	-84 997	-80 900	-23 100	-20 069	-17 525	42 002	1 571	57 753
	Shoreface	245 457	259 019	267 552	235 126	246 057	13 545	22 056	-10 541	380	6 883	-27 722	-14 406	-36 375	10 798
	Sea floor	100 677	82 034	87 398	74 517	64 595	-18 763	-13 257	-25 738	-35 826	4 665	-8 806	-18 069	-14 296	-9 868
Ostend	Dry beach	5 741	25 750	37 025	52 131	104 912	20 276	31 145	46 400	99 343	10 327	22 689	77 328	12 102	53 082
	Intertidal	25 645	-90 790	-133 466	-129 848	268 988	-116 461	-159 119	-155 502	243 309	-44 256	-44 317	358 439	-1 953	398 689
	Shoreface	318 725	401 362	443 140	392 255	486 144	80 967	122 478	71 535	165 495	38 378	-13 066	81 600	-59 197	93 681
	Sea floor	132 913	144 873	176 046	160 870	150 703	11 554	43 109	28 204	17 779	30 200	15 093	4 893	-18 770	-10 308

Table 5 – Volume differences matrix between all surveyed years and all along- and cross-shore divisions (in m^3), normalized for the surface of every unit (in m^2). Colour code correspond to the one used in Figure 12 to Figure 23.

		14-13	15-13	16-13	17-13	18-13	15-14	16-14	17-14	18-14	16-15	17-15	18-15	17-16	18-17
Middelkerke	Dry beach	0.07	0.22	0.30	0.29	0.39	0.14	0.23	0.22	0.31	0.08	0.08	0.17	-0.04	0.10
	Intertidal	0.05	0.08	0.07	0.12	0.14	0.03	0.02	0.07	0.09	-0.01	0.05	0.05	0.04	0.01
	Shoreface	0.02	0.01	0.09	0.01	-0.01	-0.01	0.07	-0.01	-0.03	0.08	0.00	-0.03	-0.09	-0.03
	Sea floor	0.00	0.01	0.06	-0.04	-0.09	0.01	0.06	-0.03	-0.09	0.04	-0.04	-0.10	-0.10	-0.06
Raversijde	Dry beach	0.15	0.39	0.60	0.66	0.65	0.24	0.45	0.51	0.56	0.20	0.24	0.31	0.03	0.06
	Intertidal	0.26	0.57	0.43	0.47	0.34	0.31	0.16	0.20	0.15	-0.15	-0.11	-0.16	0.03	-0.05
	Shoreface	0.03	0.15	0.30	0.22	0.24	0.11	0.27	0.19	0.17	0.15	0.07	0.05	-0.09	-0.02
	Sea floor	0.01	0.06	0.17	0.09	0.08	0.05	0.16	0.08	0.04	0.10	0.02	-0.02	-0.09	-0.04
Mariakerke	Dry beach	0.83	0.98	1.11	1.15	1.13	0.16	0.28	0.31	0.30	0.11	0.13	0.13	0.01	-0.01
	Intertidal	0.93	0.61	0.52	0.54	0.82	-0.32	-0.41	-0.39	-0.11	-0.10	-0.09	0.20	0.01	0.28
	Shoreface	0.66	0.70	0.72	0.63	0.66	0.04	0.06	-0.03	0.00	0.02	-0.07	-0.04	-0.10	0.03
	Sea floor	0.68	0.56	0.59	0.50	0.44	-0.13	-0.09	-0.17	-0.24	0.03	-0.06	-0.12	-0.10	-0.07
Ostend	Dry beach	0.03	0.12	0.18	0.25	0.51	0.10	0.15	0.22	0.48	0.05	0.11	0.37	0.06	0.26
	Intertidal	0.07	-0.25	-0.37	-0.36	0.75	-0.32	-0.44	-0.43	0.68	-0.12	-0.12	1.00	-0.01	1.11
	Shoreface	0.48	0.60	0.66	0.59	0.73	0.12	0.18	0.11	0.25	0.06	-0.02	0.12	-0.09	0.14
	Sea floor	0.35	0.38	0.47	0.43	0.40	0.03	0.11	0.07	0.05	0.08	0.04	0.01	-0.05	-0.03

Table 6 – The volumes of sand remaining after nourishment realised in 2013-2014 considering an efficiency of 85% of the sand volumes measured on the ship.

Sand volumes m^3	Middelkerke	Raversijde	Mariakerke	Ostend
Total nourished until survey 2014	0	68,000	670,693	797,428
Beach		68,000	477,020	383,435
Shoreface		0	193,673	413,993
Volume left 2014	29,837	72,040 **106%**	587,259 **88%**	483,024 **61%**
Volume added in 2014 after survey		162,265		
Volume left in 2015	38,025	193,208 **84%**	525,589 **78%**	481,195 **60%**
Volume left in 2016	101,029	251,887 **109%**	527,779 **79%**	522,745 **66%**
Volume left in 2017	46,719	224,035 **97%**	488,904 **73%**	475,408 **60%**
Volume added in 2018				360936
Volume left in 2018	23,877	205,944 **89%**	546,876 **82%**	1,010,748 **87%**

During period 2013 – 2014 a total volume of 1,807,200 m^3 of sand was nourished to the study zone. Apart from the morphological processes, there are also practical reasons for the loss of the initially nourished sand volume. Houthuys (2012 and 2019) estimates a typical loss of the nourished volume of 15% due to sand compaction (water and air expelled from the porous area existent in the sand), reporting and measurement errors. Accounting for these losses the total initial volume is estimated at 1,536,120 m^3. Three years after 1,188,347 m^3 of sand is still present in the area, this representing an average efficiency of 77% for the areas Raversijde, Mariakerke and Ostend. For Middelkerke there is no calculation of the efficiency since there was no nourishment carried out in that area. However, this area probably received sand from the nourishment realized just updrift in 2014 (no. 9, Table 1) explaining the rise in volume in 2016. Raversijde area shows the best efficiency and this can be explained by the relatively low volume of sand placed here but also by the constant supply of sand from the updrift area. Mariakerke has an average efficiency caused by a large amount of sand deployed here over a larger part of the beach profile increasing the sediment transport. Ostend area show the lowest efficiency and the most probable explanation is related to the accumulation of sand outside of the control box, defined for the bathymetry of 2013. In the years following the sand accumulated in this area very rapid also promoting the transport around the port due to increasing shallower water depths (Figure 24).

The volumes of sand at the two adjacent areas have a very different evolution (Figure 25): Middelkerke has a rather constant evolution while the Ostend area starts with a decrease of the sand volume and it continues with an increase in the volume due to both natural circulation of the net alongshore, but also due to human interventions such nourishments in the vicinity of the study zone. The two areas subject of the nourishment experiment have also a different evolution. For the Raversijde area the increase at the beginning of the period is explained by the later beach nourishment, therefore not recorded in the comparison 2013 – 2014. The later evolution is normal, with constant, but slow loss of sand. At the Mariakerke the evolution is the most dynamic because the largest amounts of sand were deployed here, placing the active beach out of the local equilibrium and resulting in rapid erosion in the first year. The later evolution show a slight increase for the sand volume due the influx from Raversijde area and then slightly decrease.

Figure 24 – The submerged (during high tide) groin attached to the southern jetty of the Ostend port which is trapping large volumes of sand (Google Earth 2019).

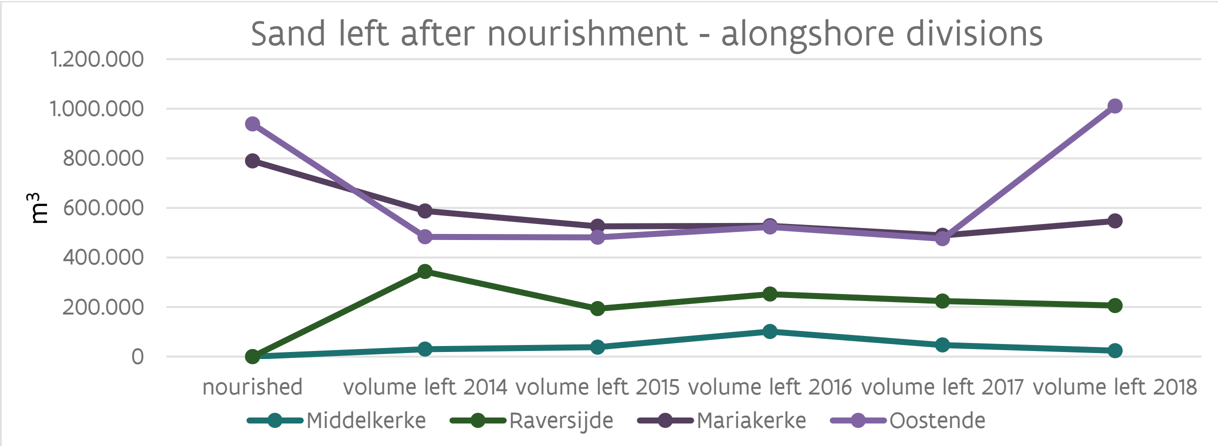


Figure 25 – Variation of the nourished volumes at the study zone.

The possible causes for the 23%, approximately 347 000 m^3, sand loss from the study zone three years after the nourishments are listed below in the estimated order from larger to smaller:

1. Sand circulating alongshore towards NE, further from the partially submerged groin attached at the lee side to Ostend port southern jetties.
2. Aeolian transport transporting sand over the landward boundary of the active beach.
3. Small losses offshore, not visible on the digital elevation models comparison since they are below the margin error for topo-bathymetric surveys and processing error.
4. Further compaction due continuous re-arranging of the nourished sand.
5. Accommodation space created by the sea level rise.

4.2 Normalized volumes

In order to compare the evolution of different parts of the study zone it was to necessary to normalize the values by calculating the volume per surface unit (m^2). The results are presented in the Table 5, Figure 26 and Figure 27.

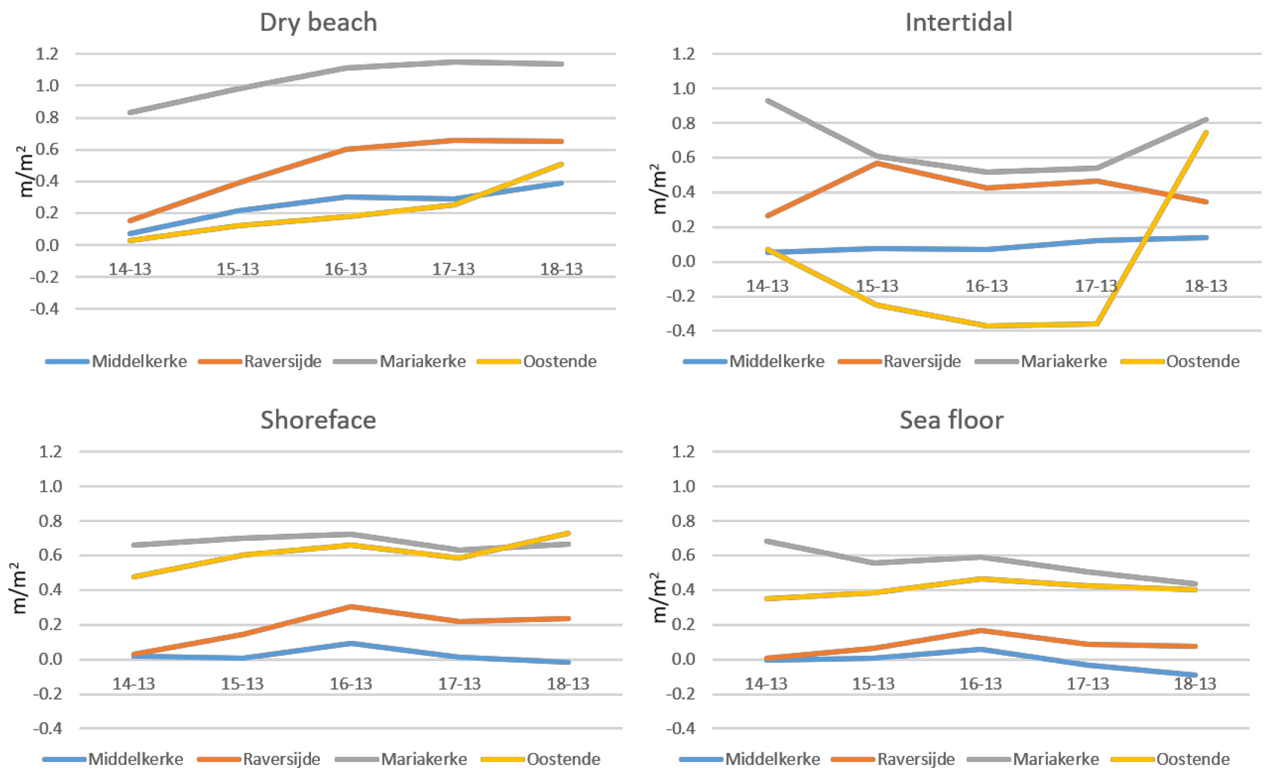


Figure 26 - Evolution of the four beach parts having as reference the pre-nourishment situation.

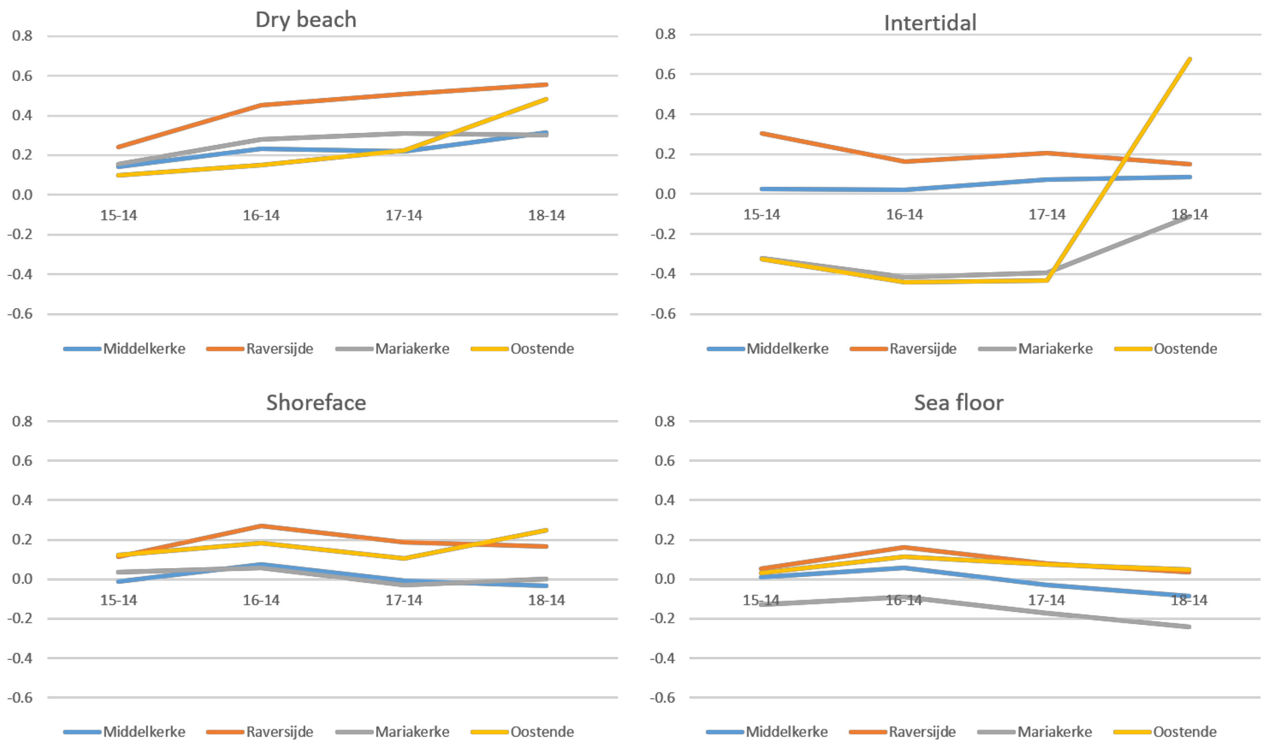


Figure 27 - Evolution of the four beach parts having as reference the post-nourishment situation.

Evolution of the sand volumes was investigated also for the cross-shore divisions of the active beach aggregated for all four areas (Figure 26 and Figure 27). Only the intertidal beach show consistent evolution with rapid initial volume decrease due to the fact that the majority of the beach nourishment was placed in this area, so easier to erode in the initial stage. However, in the later years this area start to accumulate sand, most probably as results of human interventions (local redistribution of sand, additional nourishments). Although at slower pace, the dry beach volume increased in the three years of its post-nourishment evolution, mostly due to the aeolian transport. The shoreface and sea floor sectors display a very similar evolution, with a gain in volume in the first two years and loss in the last year. Probably, the sand lost from this area can be found close to the port jetty accumulating further seaward, outside of the study area as it was defined before the nourishment experiment. The extension of Ostend port was performed relatively recent, in 2011, therefore the accommodation space created here is still to be filled out in the next years, as these jetties are impermeable to the alongshore sediment transport. However, accumulation against the jetties created a shallow area which make possible the transfer of sediments outside of the study zone.

4.3 Coastal evolution trends

The nourishments carried out at the study zone between 2013 and 2018 strongly influenced the evolution of the entire active beach. In order to evaluate the changes in relation with the beach trend evolution during a longer period a comparison in trends was made for three periods: 2006 – 2019, 2013 – 2017 and 2014 – 2017 (Table 7).

The coast evolution trends were calculated for the period 2006 to 2019 by Houthuys et al. (2019). The active beach was divided in two parts, mainly based on the survey method: dry and intertidal beach measured twice a year using a LIDAR system and shoreface and sea floor measured yearly using mostly single beam system, but also on the definition of the coastal divisions (Figure 7). The trends for the active beach were calculated for two distinctive parts: 1) the emerged beach including the dry and intertidal beach and 2) the submerged beach including the shoreface and the sea floor. The trends were calculated for two situations, first for the corrected volumes, so the sand supplied or dredged from the system by human activities was subtracted and secondly, for the observed volumes as they were measured on the active beach.

In the present study the approach was different, the volumes of sand were expressed in two ways, first as total per sediment budget box and then as volume per unit of surface in order to detect the changes in beach morphology due to the nourishments performed at the study zone. However, to compare the beach evolution trends on a longer period to the shorted post-nourishment period (3 years) the volumes of sand were expressed in the same way as in Houthuys et al. (2019). Two periods were defined for comparison: 2013 pre-nourishment to 2017 and 2014 post-nourishment to 2017 (Table 7).

It is clear that the beach trends for the period 2013 to 2017 are showing an increase in volume when compared to a longer period (2006 – 2019) due to the large volumes deployed in the area. Even areas such as Middelkerke with no nourishment of sand nourished show a reversed trend with most of the beach parts increasing in volume. The cause of this trend is the large nourishment carried out just updrift of Middelkerke in 2014 (no. 9 in Table 1). However, the submerged beach in this area is losing sand, but at slower rate than on the longer period.

At Raversijde despite the low volumes of sand nourished, there is a clear reversal of the trends from erosive on long term to accumulative for the short post-nourishment time period.

At Mariakerke there is a clear trend of erosion for the long period and this trend was reversed or slowed down by the large volumes of sand deployed here. This large volume also led to faster redistribution of this sand after nourishment, but three years after the nourishment the trends are still of a strong increase for the entire active beach. Evolution of the nourishment after 2014 show that the sand is still removed from the this area, but at slower rates than for the longer period. The area losing most of the sand is the intertidal beach while the shoreface nourishment is eroding at modest rates, 10 – 20 times lower than before. The loss of sand from the sea floor is significant, but it is believed that this loss is supporting the inshore migration of the shoreface sand bar/s.

At Ostend area the erosive trend observed for the longer period was also reversed by the nourishments. Most of the beach still show considerable increase for the short period, excepting for the intertidal beach where a decrease in volume was observed. This evolution is partially natural due to inherent re-organisation of the nourishments, but also due to human activities related to beach preparation for various activities.

Comparing the evolution of the beach evolution trends for two periods, long term (2006 – 2019) term and medium term (2013 – 2017) at the entire study zone show generally reversion of the coastal trends from erosive to accumulative, indicating the success of the nourishment. There is still some erosion in some beach sector, but at much lower rates than before. This erosion area were inevitable as the sand is redistributed in the nearshore system with clear morphological trends, the same as those observed in the DEMs comparisons:

1. Accumulation at the dry beach.
2. Intertidal beach, accumulation at Middelkerke and Raversijde, erosion at Mariakerke and Ostend.
3. Shoreface: accumulation at Raversijde and Ostend, erosion at Middelkerke and Mariakerke.
4. Stability of the sea floor, except for Mariakerke.

Table 7 - Comparisons between the measured beach trends for the medium term (report Houthuys, 2019) and the trends for short term (2013 to 2017) at the study zone. Location of the sections in Figure 10.

Sections	Report Houthuys, 2019 Period from 2006 to 2019 in $m^3/m/year$				Present study in $m^3/m/year$							
	Corrected volumes		*Observed volumes*		*Trend pre-nourishment 2013 to 2017*				*Trend post-nourishment 2014 to 2017*			
	Dry and intertidal (emerged)	Shoreface and sea floor (submerged)	Dry and intertidal (emerged)	Shoreface and sea floor (submerged)	Dry beach	Intertidal beach	Shore face	Sea floor	Dry beach	Intertidal beach	Shore face	Sea floor
Middelkerke 88-92	**Increase** +3.5	**Decrease** -16.3	**Increase** +9.78	**Decrease** -16.3	**Increase** +1.1	**Increase** +5.0	**Increase** +1.0	**Decrease** -1.1	**Increase** +1.1	**Increase** +4.0	**Decrease** - 0.8	**Decrease** -1.3
	Trend entire beach: **decrease** -16.3		Trend entire beach: **decrease** -6.5									
Middelkerke 93 – 97	**Decrease** -0.5	**Decrease** -20.5	**Increase** +5.5	**Decrease** -20.5								
	Trend entire beach: **decrease** -20.9		Trend entire beach: **decrease** -14.9		Emerged beach: **increase** +3.1		Submerged beach: **decrease** -0.1		Emerged beach: **increase** +2.5		Submerged beach: **decrease** -1.1	
Middelkerke 88 - 97	Trend entire beach: **decrease** -18.6		Trend entire beach: **decrease** -10.7		Trend entire beach: **increase** +1.5				Trend entire beach: **increase** +1.5			
Raversijde 98-102	**Decrease** -5.6	**Decrease** -10.8	**Decrease** - 5.0	**Decrease** -8.4	**Increase** +9.6	**Increase** +16.1	**Increase** +14.8	**Increase** +2.0	**Increase** +9.8	**Increase** +9.4	**Increase** +16.8	**Increase** +2.4
					Emerged beach: **increase** +12.9		Submerged beach: **increase** +8.4		Emerged beach: **increase** +9.6		Submerged beach: **increase** +9.6	
	Trend entire beach: **decrease** -16.4		Trend entire beach: **decrease** -13.4		Trend entire beach: **increase** +10.7				Trend entire beach: **increase** +9.6			
Mariakerke	**Decrease** -13.9	**Decrease** -18.1	**Decrease** - 36.9	**Increase** +11.5	**Increase**	**Increase** +20.9	**Increase** +44.5	**Increase** +14.1	**Increase**	**Decrease** -20.4	**Decrease** - 2.7	**Decrease** -6.5

103-105	Trend entire beach: decrease -32.7	Trend entire beach: decrease -25.3	+13.0 Emerged beach: increase +17.0 Submerged beach: increase +29.3 Trend entire beach: increase +23.2	+4.70 Emerged beach: decrease -7.9 Submerged beach: decrease -4.6 Trend entire beach: decrease -6.3
Ostend 106-108	Decrease -15.8 Decrease -6.6 Trend entire beach: decrease -22.5	Decrease -51.3 Increase +9.5 Trend entire beach: decrease -41.9	Increase +5.0 Decrease -12.3 Increase +37.3 Increase +15.3	Increase +5.9 Decrease -19.7 Increase +9.1 Increase +3.6
Ostend 109-112	Increase +1.8 Decrease -23.9 Trend entire beach: decrease -22.1	Decrease -66.5 Decrease -6.9 Trend entire beach: decrease -73.4	Emerged beach: decrease -3.7 Submerged beach: increase +26.3	Emerged beach: decrease -6.9 Submerged beach: increase +6.3
Ostend 113-117	Decrease -14.5 Decrease -20.0 Trend entire beach: decrease -34.5	Decrease -39.9 Increase +16.4 Trend entire beach: : decrease -23.5		
Ostend 106 – 117	Trend entire beach: decrease -26.4	Trend entire beach: decrease -46.6	Trend entire beach: increase +11.3	Trend entire beach: decrease -0.3

5 Alongshore transport estimation

Investigation of the beach evolution post-nourishment is better understood if insight into the along and cross-shore transport is obtained. To calculate the alongshore sediment transport as well as making prediction for the future decade the 1D process-based numerical model Unibest model was used.

The available data of the topography and bathymetry in the nourishment site is used to analysis the morphological changes. Overview of the data can be found in Dan et al., 2016. The data were processed with ArcGis software to get rasters of 10 m resolution (Dan et al., 2016). Overview of the considered coastal areas and sections can be seen in Figure 10. Coastal sections 91-97 are considered as Middelkerke coastal area. Raversijde covers the section from 98 to 102. Sections 103, 104 and 105 are located in Mariakerke and sections close to the Ostend port (106-115) are called Ostend.

In the analysis, the evolution of the morphological changes over the five-year period, 2013-2018 will be analysed, focusing on the changes of the coastline and cross-sections. The two areas Raversijde and Mariakerke are of the main interest. The two sections (profiles) 100 and 104 are selected as the representative profiles for the two areas. Section 100 represents the case of only beach nourishment while both beach and shoreface nourishments were conducted at Section 104.

5.1 Coastline changes

5.1.1 Definition of Momentary Coastline

For the purpose of the analysis of the coastline changes and setting up of Unibest-CL model (Section 6), this study applies the concept of the Momentary Coastline - MCL (in Dutch: Momentane Kustlijn - MKL) developed by Ministerie van verkeer en waterstaat (1991) (Figure 28).

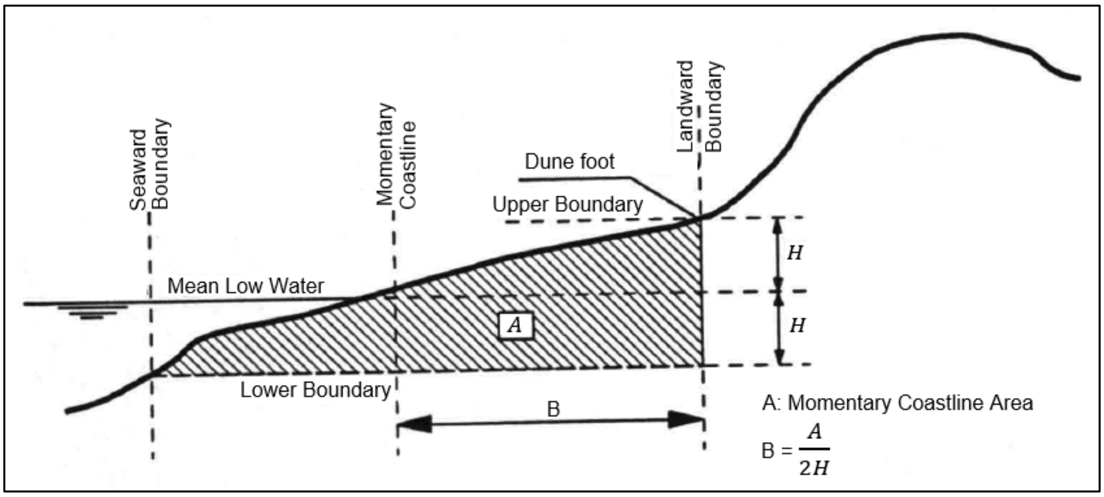


Figure 28 – Definition of Momentary Coastline (after Ministerie van verkeer en waterstaat, 1991).

The calculation of MCL for the study area is done for the representative profiles of all coastal sections. One profile within each coastal section is chosen in the calculation.

The MCL for the study area is defined as follows: first the dune foot is identified following Houthuys (2012) with the dune foot level of +6.89m TAW for the Flemish coast. The horizontal upper boundary and landward boundary are located at this dune foot or at the level that the beach meets the dike if this level is lower than +6.89m TAW (Figure 28). The height H from the upper boundary to Mean Low Water line (+1.39m TAW) is then calculated to be 5,5m. The horizontal lower boundary is at the vertical distance of 2.H (11m) from the upper boundary, so at -4,11 m TAW. The intersection of the bed level and the lower boundary is the location of the seaward boundary. The momentary coastline area A is defined as the area bounded by the landward boundary, lower boundary and the bed level. Finally, the Momentary Coastline position is determined basing on the distance B from the landward boundary with $B = \frac{A}{2H}$ (Figure 28).

5.1.2 Medium-term evolution of the MCL

In Figure 29 the evolution of the Momentary Coastline (MCL) is presented for the period of five years: 2013-2018. The MCL position is presented as the distance of the calculated MCL from the dike. The MCL is calculated for the cross-shore profiles (one per coastal section) extracted from the available topography and bathymetry data.

As during the period 10/2013-02/2014, beach nourishment campaigns were carried out in the section 102-106 (681 200 m^3) and 109-115 (822 200 m^3), and 190 900 m^3 of sand was released on the beach of sections 97-102 in 06/2014, the coastline in 2014 at those coastal sections is more seaward compared to 2013 (Figure 29). The largest shift of the MCL is found for the Mariakerke coastal area (section 103-105) which is in the range of 25-50 m.

After the nourishment campaigns, the nourishment redistribution has been occurred which the nourished sand is transported to the adjacent coast. This leads to erosion of the coastal sections where nourishment took place and sedimentation at the adjacent coastal areas. The most noticeable of the coastal retreat (erosion) after nourishment is observed for section 103 which its MCL is shifted strongest due to nourishment in 2014. The erosion is largest in the first year and is reduced in time.

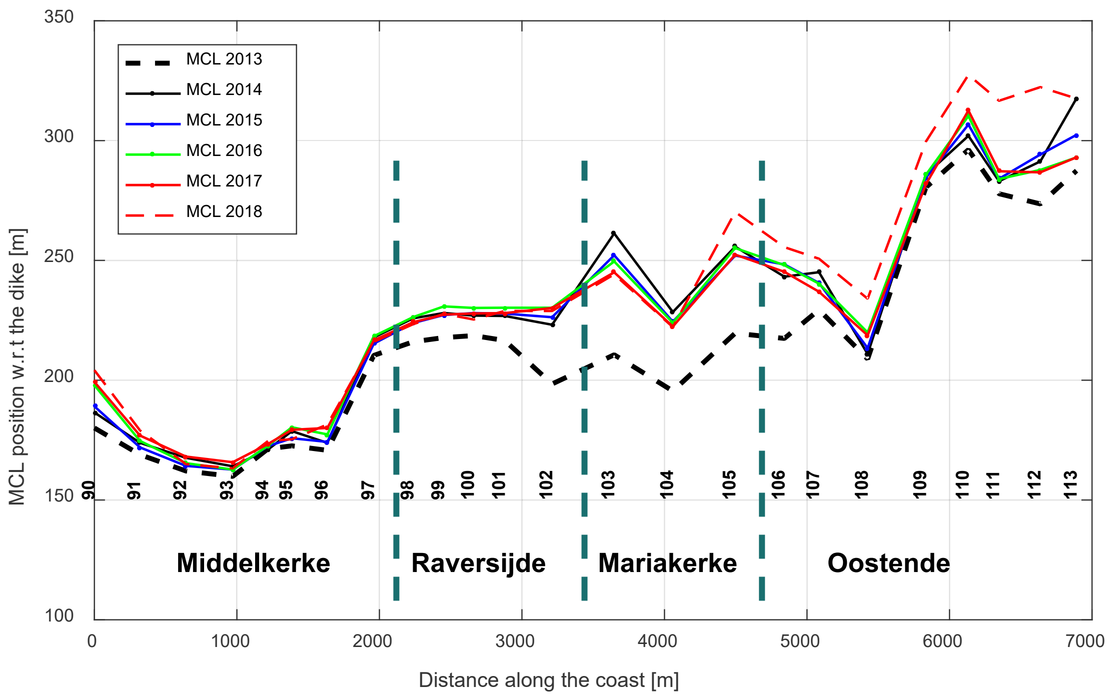


Figure 29 – Evolution of the MCL during the period 2013-2018.

In February - March 2018, beach and shoreface nourishment was carried out for sections 105-109 (315 381 m^3) and for sections 105-116 (424 631 m^3) (no. 26 and 27, Table 1). This is clearly shown up in Figure 29 for MCL of 2018 with the advance of the coastline along these sections.

5.2 Temporal variation of the profiles

5.2.1 Profile 104 (Mariakerke)

Figure 30 shows the changes of the representative cross-shore profile for the Mariakerke coastal area (profile 104, middle of the section) from 2013 to 2018. Both beach and shoreface nourishment were conducted in 2014 (see Dan et al., 2016 for the overview of the nourishment campaigns). The bathymetry in 2014 is measured in May right after the shoreface nourishment while beach topography was conducted in April, about two months after finishing beach nourishment.

As the results of beach and shoreface nourishment, the seaward movement of the profile 2014 (after nourishment) compared to that in 2013 (before nourishment) is clearly observed. The beach is widened up to 80m and the berm of about 55 m is observed at the level of -2m TAW.

After nourishment, the strongest morphological changes are observed in the first year 2014-2015. The nourished beach was eroded and the shoreface nourished sand seems to be transported landward. The nourished sand on the beach eroded and could be transported in alongshore and cross-shore. The artificial sand berm (as the result of shoreface nourishment) moved landward and raised about 1m to the level of -1.5m TAW after one year. The process continued in the next year in 2016. Little change is observed in the year 2016-2017. In 2018, the berm returned to its position of 2015.

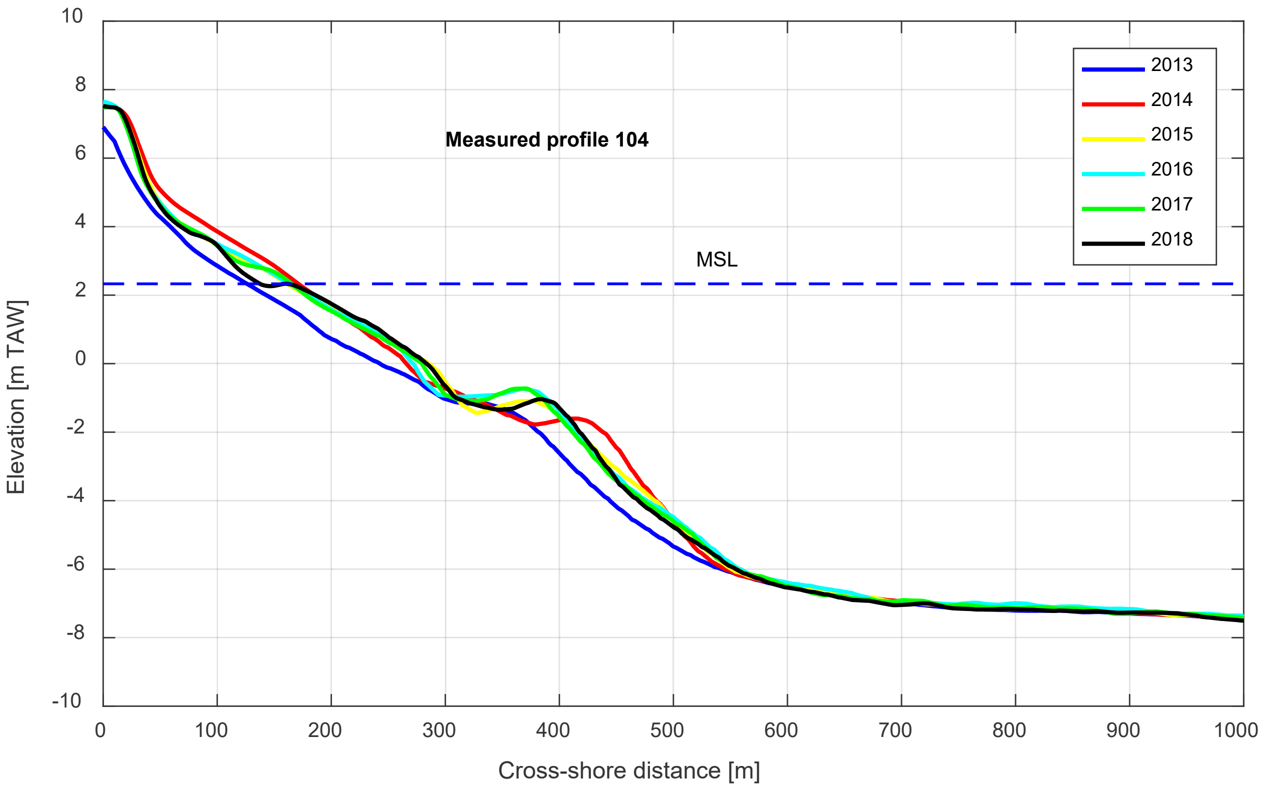


Figure 30 – Evolution of the cross-shore profile at Mariakerke: profile 104.

5.2.2 Profile 100 (Raversijde)

The changes of the profile 100 located in Raversijde (middle of the section) are also analyzed (Figure 31). This profile represents for the coastal area where only beach nourishment was carried out (in June 2014). Note in this analysis that the topo-bathymetry of the beach in the Raversijde area for 2014 was conducted in November (i.e. five months after beach nourishment campaign in June 2014).

Compared to the profile in 2013, the one in 2014 moved seaward due to beach nourishment in June 2014. The changes is much smaller than that for Mariakerke case. This is mainly is due to the fact that the amount of nourished sand is smaller for Raversijde and the topography used in the analysis is measured much longer after conducting beach nourishment for Raversijde than for Mariakerke.

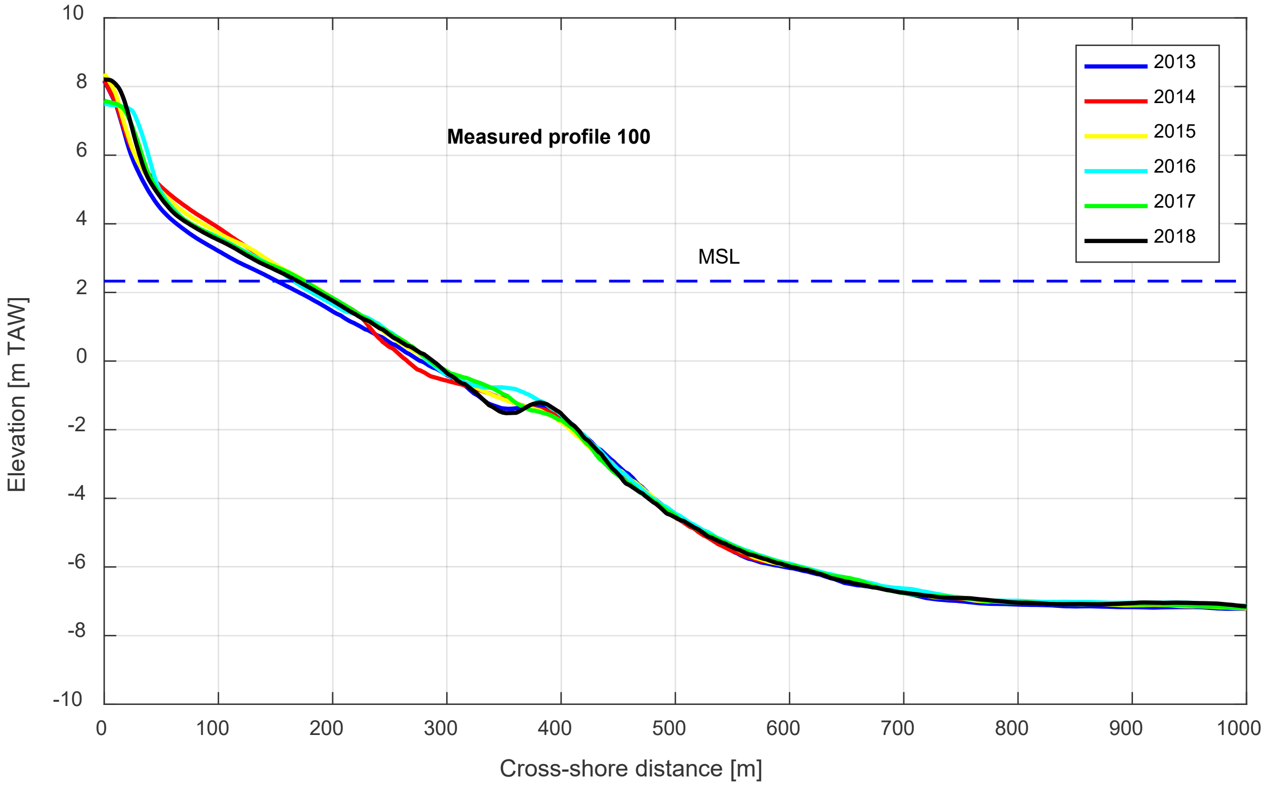


Figure 31 – Evolution of the cross-shore profile at Raversijde: profile 100.

6 UNIBEST model

UNIBEST-CL+ consists of two sub-modules:

- The Longshore Transport module (UNIBEST-LT) calculates tide and wave induced longshore sediment transport
- The CL-module simulates coastline changes due to longshore sediment transport gradients along the considered coast.

6.1 UNIBEST CL+ model set-up

In this study, focus is on modeling the evolution of the coastline of the coastal areas Mariakerke and Raversijde. To gain this aim, the UNIBEST-LT model is setup first. The relation between coast angle and longshore sediment transport (the S-Phi curve) is determined within the UNIBEST-LT module. This S-Phi curve is then used as an input of the UNIBEST-CL module to compute the coastline evolution.

Two models are setup for the study area for the purpose of model calibration and prediction are presented briefly in Table 8. In both calibration and prediction runs, one representative cross-shore profile and the same wave climate are applied for the whole model domain. Therefore, the sediment transport gradients are only due to the changes in the coastline orientation.

Details of the model setup is illustrated in the following sections.

6.1.1 Coastline angle

The angle specified in UNIBEST-LT is the angle of the offshore directed coast normal of the coastline (degrees North). It is used for the schematisation of the relation between coast angle sediment transport. In the area of Mariakerke, the coast normal angle relative to North is about 325° (Figure 32).

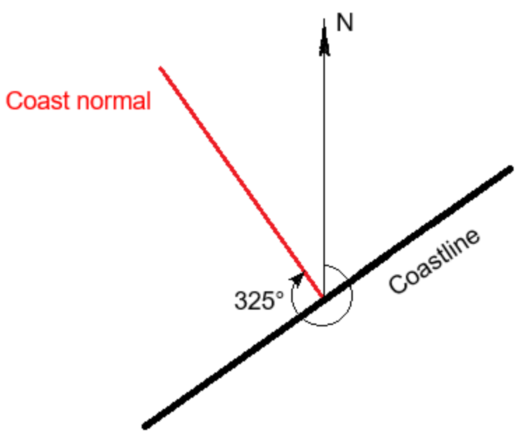


Figure 32 – Coastline angle implemented in UNIBEST-LT.

6.1.2 Cross-shore profile and active height

The impact of variation of the cross-shore profile shape in alongshore direction is smaller than the influence of many other parameters such as the use of nearshore wave climate conditions or the selection of a transport formulation (Huisman, 2014). In Section 5.2 the temporal and spatial variation of the cross-shore is observed, but cross-shore profile shape does not change significantly within the study area. It is decided to choose the cross-shore profile 104 as the representative profile for the whole study area.

The active height of the profile influences the time scale at which coastline changes (e.g. retreat, accretion or re-orientation) take place. In UNIBEST, it has to be specified on the basis of estimates of the depth of closure (Huisman, 2014).

Applying Hallermeier (1981) formulation, Vandebroek et. al (2017) calculated the depth of closure for the whole Belgian coast. The closure depth value of about -5.15 m TAW was found for the coastal area between Middekerke and Ostend port.

The depth of closure is also estimated based on the bathymetry measurement. In §5.2.1, the temporal variation of the cross-shore profiles over the six years 2013-2018 are analysed. It is found that there is almost no change in the bed over 6 years at the level deeper than -6 m TAW ÷ -6.5 m TAW.

It is decided to choose the closure depth at the level -6.5 m TAW. The active height is set as the height from closure depth level (-6.5 m TAW) to active upper limit. This active upper limit is defined as Mean Sea Level (+2.33 m TAW) plus spring tidal range at Ostend (4.7m). The resulting active height is 13.5 m.

Figure 33 presents the cross-shore profile applied in UNIBEST-CL+ for the whole model domain. The bottom profile is schematised at 10 m intervals using extract data from topo-bathymetry measurement at the section 104. As the wave data at Raversijde station will be used as the boundary condition of the model. This station is located at about 740 m at a depth of about -7 m TAW. The dynamic boundary is set at this location. The longshore transport is computed up to this boundary.

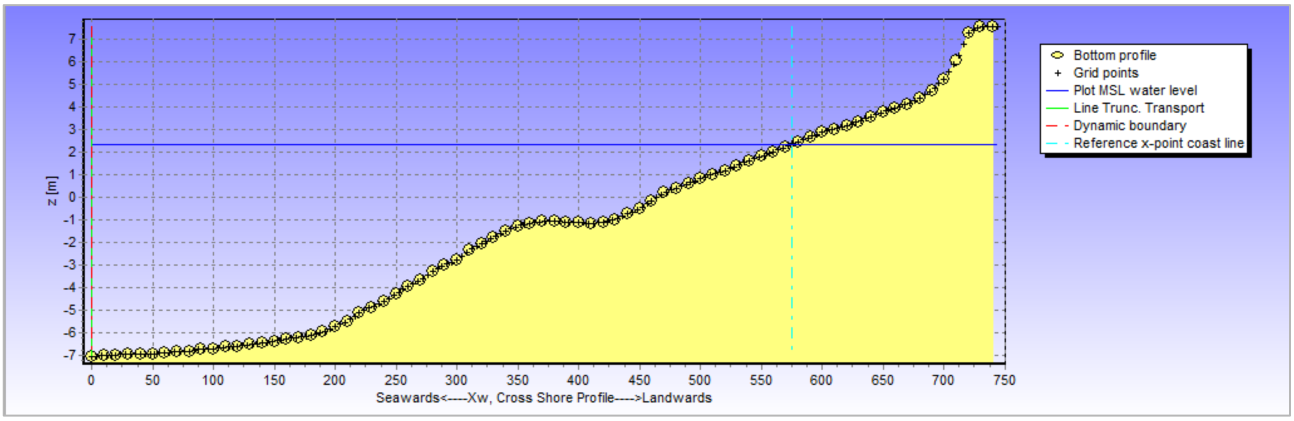


Figure 33 – Cross-shore profile implemented in UNIBEST-CL+.

6.1.3 Simulation period

For the evaluation of the model, the simulation period is chosen based on the nourishment situation in the area and the availability of the topography and bathymetry data with the main interest on the Mariakerke and Raversijde coastal areas. The 3-year period, 01 July 2014 – 30 June 2017 is chosen for the calibration.

6.1.4 Wave conditions

This study uses the wave data measured with a directional wave rider at Raversijde station which is located in front of Mariakerke area, about 740 m from the dike (see Figure 37 for the location). This data is provided by Flemish Hydrography as time series of significant wave height, peak period, and wave direction at 30-minute intervals. This time series are then reduced to daily average wave height, period, direction to satisfy the requirement the UNIBEST-LT model which allows a limited number of input conditions.

Figure 34 presents the wave rose at Raversijde wave buoy, plotted using the daily wave data during the three-year period, 1 July 2014 – 30 June 2017. The full black line represents the coastline orientation. It is clear that the most predominant waves are from the west which form an angle of about 30°-50° with the coastline. The dominant wave heights are smaller than 1 m but very high waves (Hs > 2.5 m) are also observed.

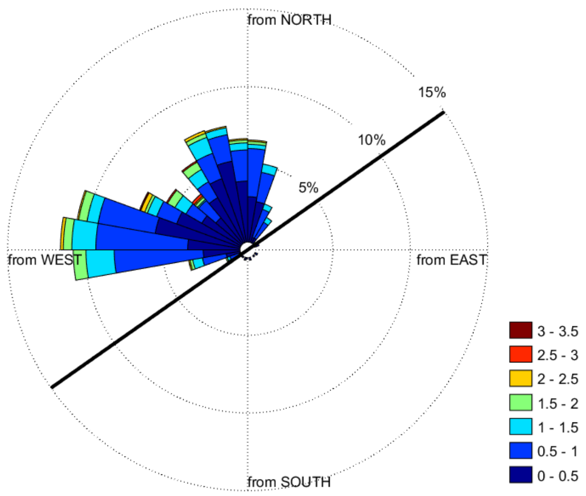


Figure 34 – Wave rose at Raversijde wave buoy during the period July 2014 – July 2017.

6.1.5 Sediment property

Deronde (2007) presented the median grain size for three positions on the beach: at the low water level, just below the high water level, and on the dry beach based on the analysis of 357 samples collected on the Belgian beach in the years 2001 and 2002 (Figure 35). The areas where beach nourishment (e.g. Knokke-Zoute) or beach scraping (e.g. Mariakerke) at that time are indicated in red and blue, respectively.

The figure shows a clear trend of the increase in grain size along the Belgian coast from the southwest (French border) to northeast (Dutch border), ranging from 170 µm to about 400 µm in De Haan and Knokke-Zoute. There is also the trend of increased grain size towards the dry beach. At Mariakerke, most of the samples show the median grain size in the range of 170-250 µm.

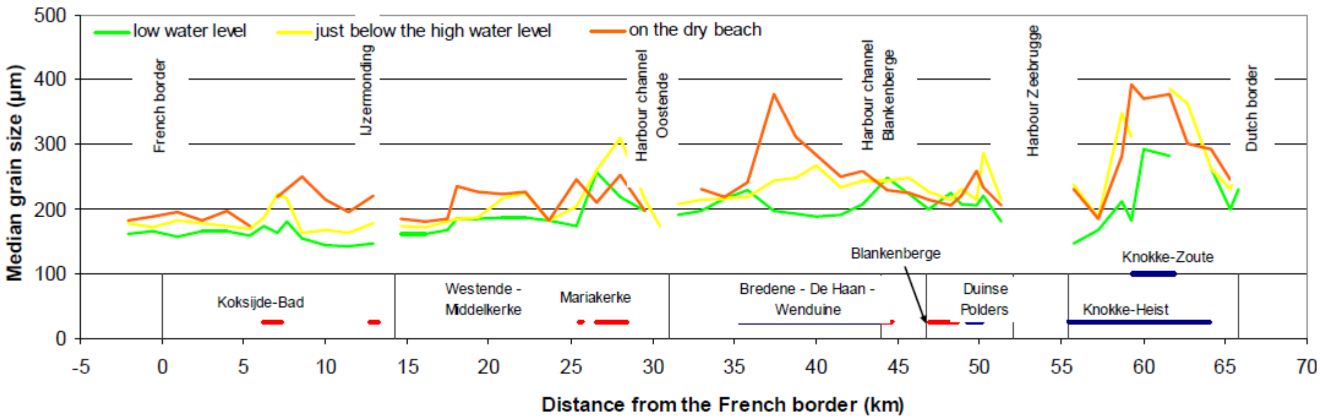


Figure 35 – Longshore variation of the median grain size for three positions on the beach (after Deronde, 2007).

In Montreuil et. al (2018), the distribution of sediment size across the beach of the coastal section 103 at Mariakerke is shown for the measured campaign on 19th March 2017 (Figure 36). Sediment samples were collected at four locations along the beach by scraping a surface layer of about 5 mm thick and analysed in laboratory for the grain size. The median grain size is varying around 300 µm which is close to the highest value for the Mariakerke reported by Deronde (2007).

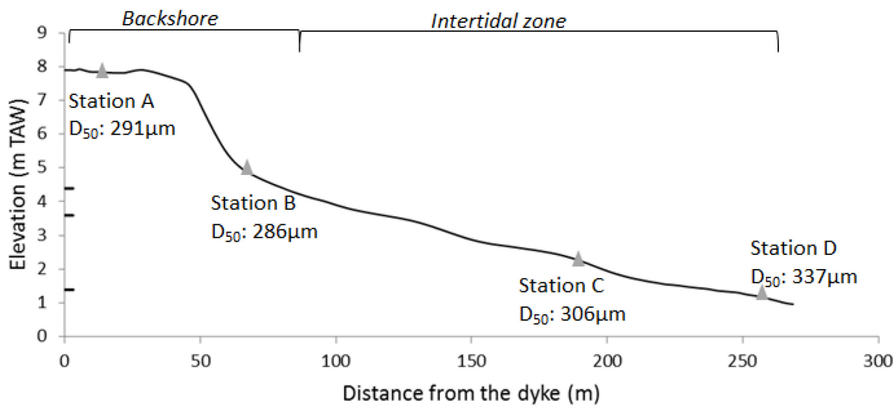


Figure 36 – Sediment characteristics across the beach topography

In this study, several sensitivity analysis/calibration runs are conducted with the different the values of D_{50} (210 µm, 300 µm).

6.1.6 Sediment transport formulation

Within UNIBEST-CL+, eight sediment transport formulae are currently available (see Deltares, 2011). In this study, sensitivity analysis is done with the application three formulations: Bijker (1967, 1971), Van Rijn (1993), Van Rijn (2004) and Soulsby-Van Rijn. Both bed load and suspended load are considered in these formulations.

Figure 37 – Unibest-CL model grid and initial coastline (2014) for calibration runs (upper) and (2018) for prediction run (lower).

6.1.7 Initial coastline and grid

The main concern of this study is to investigate the morphological evolution of the coastal area of Mariakerke and Raversijde where only beach nourishment or combined beach-shoreface nourishment took place. The coastline model Unibest-CL is therefore set-up covering the two coastal areas and extends to the southwest and northeast. The model covers about 8 km of coastline, stretching from coastal section 89 to Ostend port (right boundary). The model is constructed containing 150 grid cells with a longshore grid size of about 55 m (Figure 37).

As described in §6.1.3, the model calibration runs are conducted for the period of three years 2014-2017 and prediction runs for nine years 2018-2027. The initial coastline is the Momentary Coast Line (see §5.1.1 for the definition) which is constructed basing on the topo-bathymetry measurement for the year 2014 for the calibration runs and year 2018 for the prediction run (Figure 37).

6.1.8 Boundary condition

At the two ends of the model domain, boundary conditions have to be specified. It is assumed that there is no movement of the coastline the left end (Y = constant) of the model domain and no transport is observed over the Ostend port (Q = 0 m^3/y).

Table 8 summaries the general parameter setting of the UNIBEST-CL+ model for the study area.

Table 8 – Summary of UNIBEST-CT+ model set-up

Parameter	Calibration run	Prediction run
Simulation Period	03 years (01.07.2014 - 30.06.2014)	09 years (2018-2027)
Initial profile	Profile 104 (mean 2014-2017)	Profile 104 (measured 2018)
Initial coastline	Momentary Coastline (MCL) 2014	Momentary Coastline (MCL) 2018
Active height	13.5 m	13.5 m
Boundary condition	Left: Y = constant; right Q = 0 m3/y	Left: Y = constant; right Q = 0 m3/y
Wave climate	Raversijde daily wave data	Raversijde daily wave data
Wave parameter (Breaking, bottom friction, roughness)	Default	Default
Wave/current-related roughness, transport factor	Default	Default

6.2 Model sensitivity analysis and calibration

6.2.1 Model runs

The sensitivity analysis is done with the use different sediment transport formulation and sediment grain size. Table 9 summaries the UNIBESTCL+ calibration runs implemented for the study area.

Table 9 – Sensitivity analysis/calibration runs of UNIBEST-CL+.

RunID	D_{50} [µm]	D_{90} [µm]	Sediment transport formulae
MAR01	210	300	Bijker (1967, 1971)
MAR02	210	300	Van Rijn (2004)
MAR03	210	300	Soulsby-Van Rijn
MAR04	300	450	Bijker (1967, 1971)
MAR05	300	450	Van Rijn (1993)
MAR06	300	450	Van Rijn (2004)

6.2.2 Model results

Alongshore sediment transport (S-Phi curve)

Figure 38 shows an example of the S-Phi curve for the run using Bijker sediment transport formula (run MAR01). Depending on the coastal orientation, the longshore sediment transport can reach a maximum value of almost 200.000 m^3/year. If the coast normal angle is about 300°N, the longshore transport becomes zero.

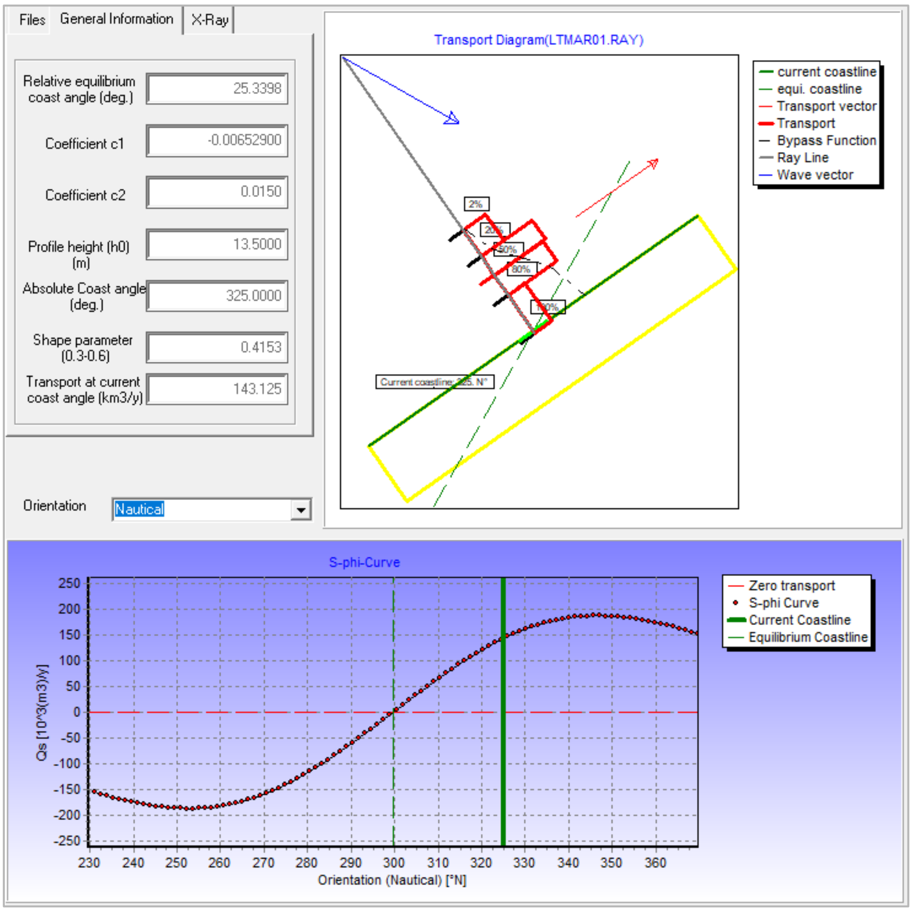


Figure 38 – Relation between coast angle and sediment transport (S-Phi curve) for run MAR01.

Table 10 presents the result of the longshore sediment transport for the current coastal orientation (i.e. coast normal angle of 325°N) for the six sensitivity analysis/calibration runs. It is clear that different sediment transport formulae result in a large differences in the along shore sediment transport. Within the model set-up, the differences is in the factor 2 to 3 as the result of the application of different transport formulations. Soulsby-Van Rijn gives very low transport value: 70 000 m^3/year for finer sand (i.e. D_{50} = 210 µm).

As expected, sediment grain size also has an effect on the longshore transport. Coarser sand leads to lower transport as it is more difficult for coarse sand to mobilize. An increase of D_{50} from 210 µm to 300 µm results in a reduction of the transport from 143.000 to 89.000 m3/year with the application of Bijker (1967, 1971) formula and from 202.000 to 160.000 with Van Rijn (2004).

In the study of Vandebroek et al. (2016), the longshore sediment transport rate has been evaluated for the whole Belgian coast using the results of the previous numerical study and applying sediment transport formulations. The uncertainty of the longshore transport rates was also investigated to consider the year-to-year variability in the transport. The net sediment transport rates of about 150.000 m^3/year towards the northeastern direction are reported for Mariakerke coastal area with the variation range of 100.000 – 200.000 m^3/year.

Among those six runs, the three runs MAR01, MAR02 and MAR06 produce the closest value of the longshore sediment transport reported in literature and will be considered in the analysis of coastline changes.

Table 10 – Longshore transport with different sediment transport formulae and grain size.

RunID	D_{50} [µm]	D_{90} [µm]	Sediment transport formulae	Qs (m3/year)
MAR01	210	300	Bijker (1967, 1971)	143 125
MAR02	210	300	Van Rijn (2004)	202 310
MAR03	210	300	Soulsby-Van Rijn	70 315
MAR04	300	450	Bijker (1967, 1971)	89 338
MAR05	300	450	Van Rijn (1993)	224 785
MAR06	300	450	Van Rijn (2004)	159 613

6.2.3 Coastline changes

Figure 39 shows the comparison of the measured and computed coastline changes after three years. The modeled results of three runs MAR01, MAR02 and MAR06 with good prediction of longshore sediment transport are considered. Focus is on the two coastal areas Ravesijde and Mariakerke.

As discussed in §5.1.2, redistribution of the nourishment is observed with the erosion in the nourished place and sedimentation in the adjacent coast. This feature is reproduced by the model with a strong morphological evolution is observed around the coastal section 102 where beach and shoreface nourishment was started. Section 103 is subjected to the strongest erosion and largest sedimentation occurs around sections 101-102. As the result of different longshore transport rate, the difference in the coastline evolution are also found between the runs.

Although the trend in the coastline evolution is generally produced by the model, there are deviations in the measured and modeled retreat and advance rate. The model underestimates the erosion for section 103 while overestimates sedimentation rate at section 102. Over the three years, the measured MCL was retreated up to about 16m while the calculated value is in the range of 7.5 - 8.5m. The maximum advance of about 7.5 m is observed and the corresponding value from the model are in the ranges 10-12 m. The differences are due to a number of factors: error in the measurement; simplification of the model set-up: use of the same wave condition alongshore, exclusion of the effect of flow, use of uniform sediment grain size.

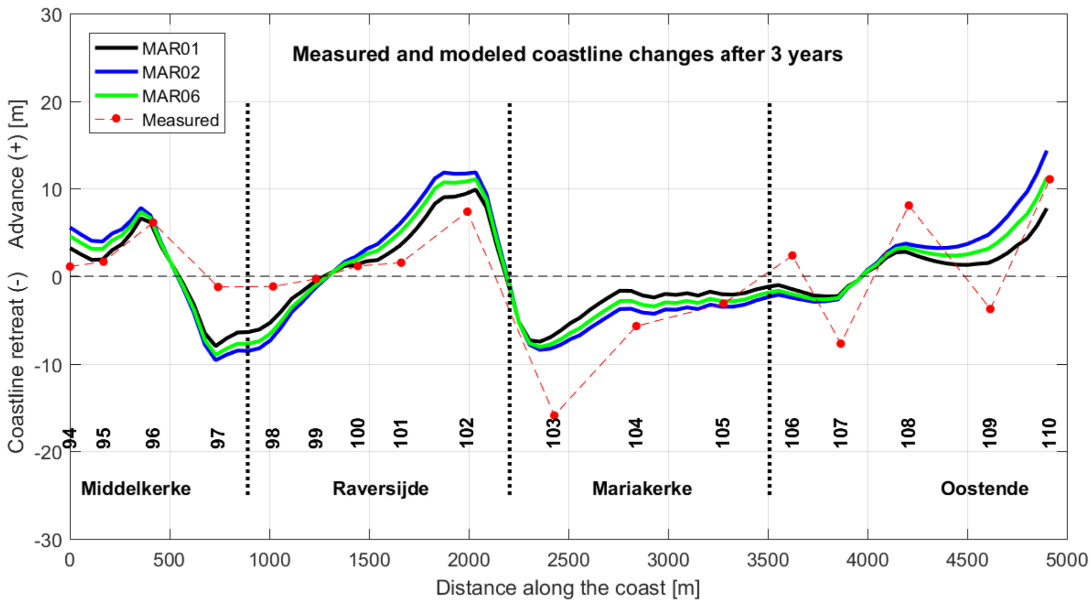


Figure 39 – Modeled vs. measured coastline changes after three years.

In Figure 40 the comparison of the yearly measured and model coastline evolution is shown for run MAR06 which produces the closest value of longshore sediment transport reported in literature for the study area. Similar to the measurement, the largest changes of the coastline are calculated in the first year and the changes are also reduced in time.

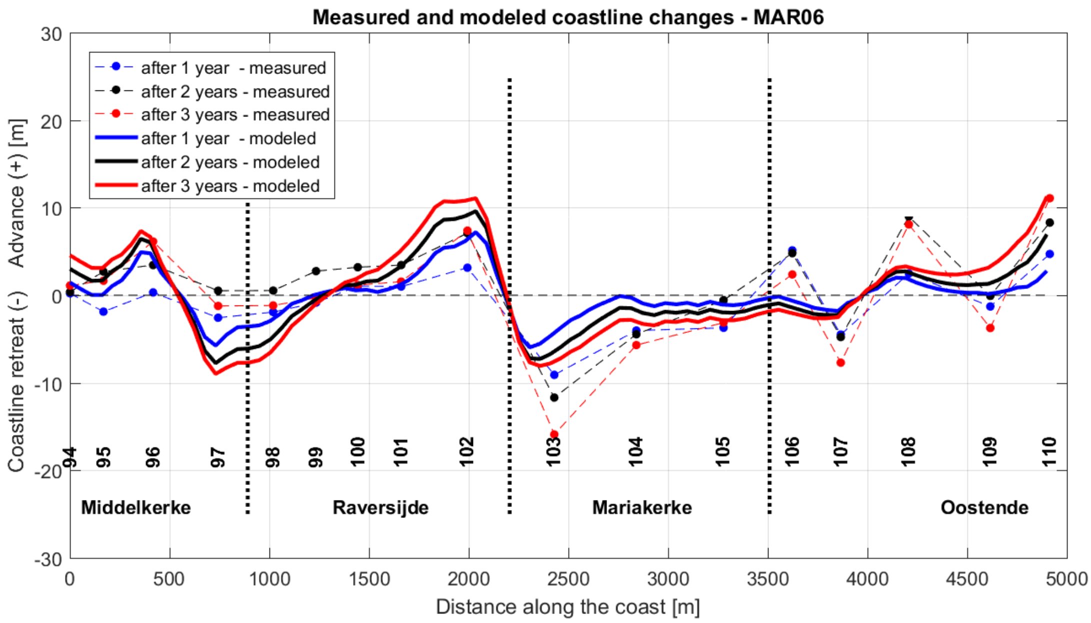


Figure 40 – Modeled vs. measured coastline changes after 3 years.

6.3 Prediction of the coastline changes

One simulation is carried out with the setting of run MAR06 which produces the closest value of the reported longshore sediment transport. This run also reproduces reasonable result in term of coastline changes in the three-year period. The model run is carried out for the period of nine years 2018 - 2027. The three-year wave data (2014-2017) at the Raversijde wave buoy are used and repeated three times to simulate the morphological changes over the period of nine years.

Figure 41 presents the prediction of the coastline changes in the period of nine years from 2018 to 2027. It is clear that the coastline changes are reduced over time. The most eroded section is 105 (Mariakerke) where beach nourishment started taking place in 11/2017 and 02-03/2018. The redistribution of the sand over time leads to erosion in this section and sedimentation in the surrounding areas.

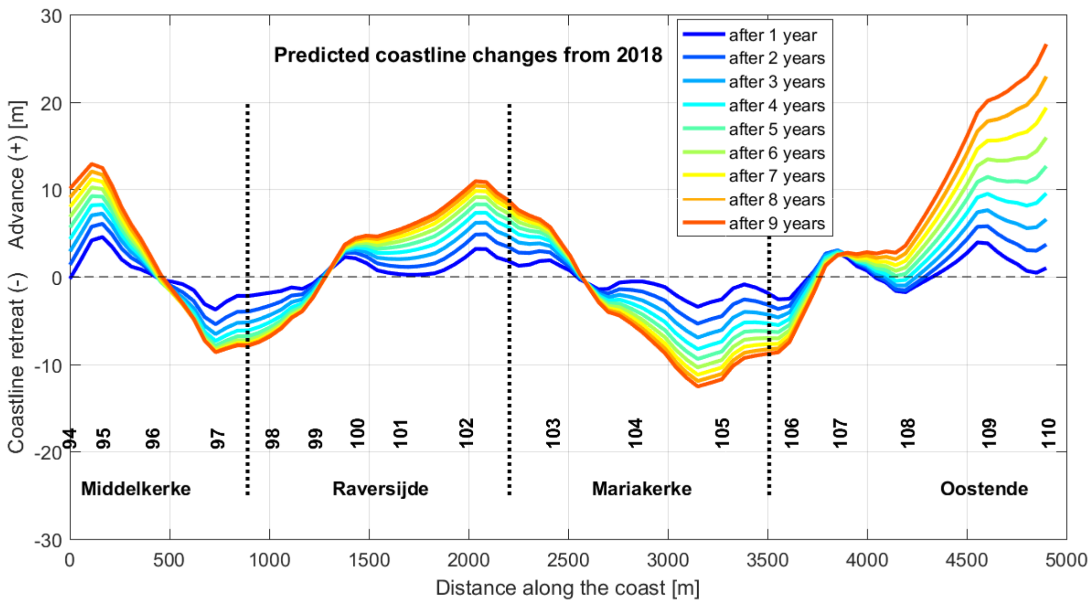


Figure 41 – Prediction of coastline changes from 2018-2027.

6.4 UNIBEST-TC model setup

UNIBEST-TC (**Uni**form **Be**ach **S**ediment **T**ransport – **T**ime dependent **C**ross shore) is a process-based model that consists of wave, current, sediment transport and bed level modules.

This section focuses on the calibration of the wave model within UNIBEST-TC and the evaluation of the influence of beach or/and shore face nourishment on the wave height in the area of Mariakerke.

6.4.1 Cross-shore profile

In the study area, the significant wave heights are available at the location within section 103 during November 2017 from the local wave buoy. This wave data will be used in the validation of the wave sub-model. The cross-shore profile 103 measured in November 2017 is used in the calibration (see Figure 42 for the location).

For the study the influence of the beach or/and shore face nourishment on the wave height, the profiles 100 (only beach nourishment) and 104 (beach + shore face nourishment) measured in 2014 are considered. Those measured in 2013 are considered as without nourishment case.

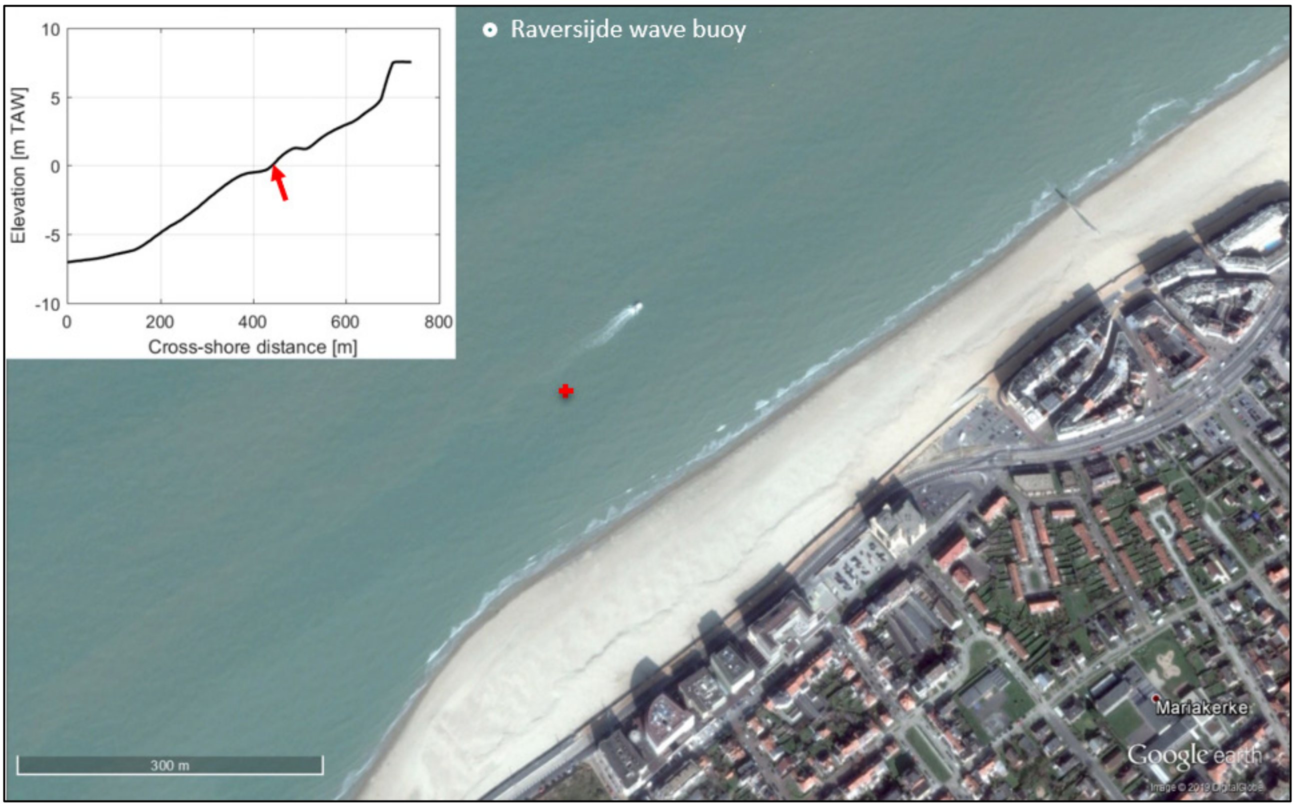


Figure 42 – Location of wave stations (red) used in the wave model validation.

6.4.2 Simulation period

The calibration simulation is done for 10 days 07/11/2017 – 17/11/2017 which measured wave data is available.

6.4.3 Boundary condition

At the model boundary, the time series of water level, wave height, wave period, wave direction is prescribed:

Water level

The measured water levels at the location closest to the area, Ostend station are used.

Wave condition

The wave height, wave period, wave angle measured at Raversijde wave station are used (see Figure 42for the location).

As the Unibest-TC model requires the root mean square wave height H_{rms} , the measured significant wave height H_s at the boundary is converted to H_{rms} : H_{rms} = $H_s/\sqrt{2}$, assuming a Rayleigh distribution.

The wave angle in Unibest-TC is defined with respect to the coastal normal as shown in Figure 43. The wave angle at Raversijde wave buoy (in degrees North) has to be converted following this convention.

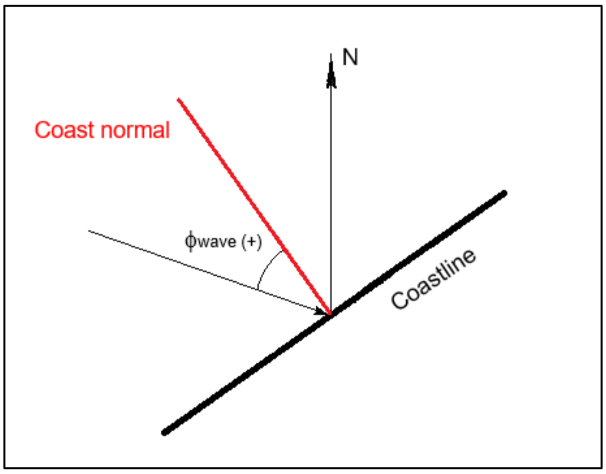


Figure 43 – Wave angle implemented in UNIBEST-TC

Figure 44 shows the wave condition at the Raversijde wave buoy during UNIBEST-TC simulation period of 10 days, 07/11/2017 – 17/11/2017. During this period, both calm and energetic conditions were encountered. The highest H_{rms} of 2 m was recorded at the end of day 6 (12/11/2017).

Most of the waves are found coming from the direction of the coastal normal or the western section with respect to the coastal normal (Figure 44, lower panel).

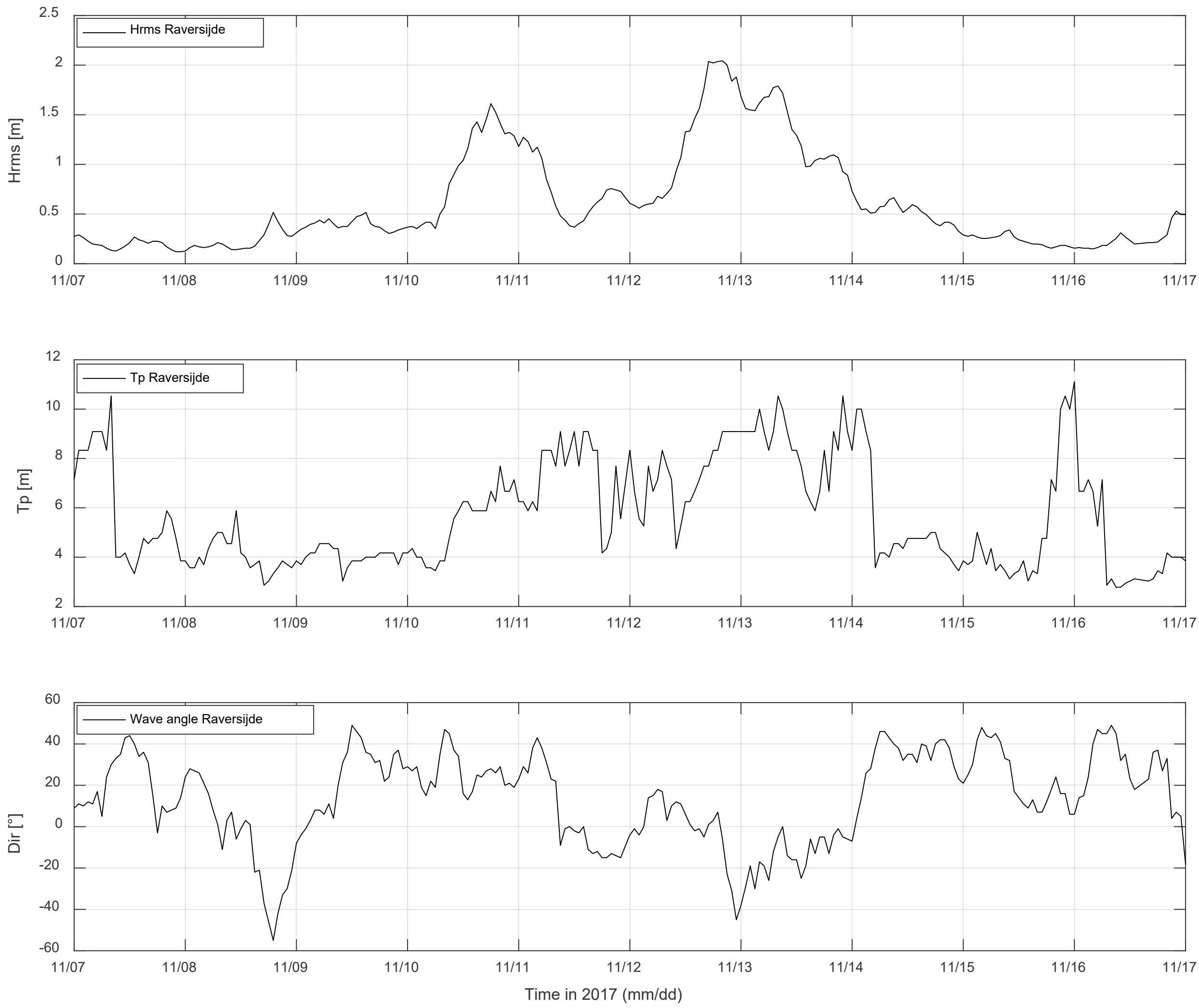


Figure 44 – Wave height, period, angle at Raversijde wave buoy used as boundary condition in UNIBEST-TC model.

6.5 Calibration of the wave model

6.5.1 Calibration runs

Four simulations have been carried out with the variation of the wave breaking parameter GAMMA, slope of wave front BETD, friction factor for bottom friction FWEE and with/without breaker delay K_IJL (Table 11). In those simulations, the bed level remains unchanged. The breaker delay modifies the rate of wave breaking via a modification of the reference depth which is used to determine the local maximum possible wave height (Walstra, 2000).

Table 11 – Calibration runs of UNIBEST-TC wave model

RunID	GAMMA	BETD	FWEE	K_IJL
utc001	0 (Battjes and Stive, 1985)	0.1	0.01	1
utc002	0.5	0.1	0.01	1
utc003	0.8	0.1	0.01	1
utc004	0.5	0.05	0.1	0

6.5.2 Calibration results

Figure 45 shows the comparison of measured and computed significant wave height at the location close to the shore, within beach section 103 (see Figure 42 for the locationWave breaking parameter GAMMA influences strongly the modeled wave height (Figure 45). Default GAMMA = 0 (Battjes and Stive, 1985 relation) (run utc001) and GAMMA = 0.8 (utc003) overestimate the wave height. The use of GAMMA = 0.5 with some adjustment of BETD, FWEE and K_IJL (utc004) produces a reasonable agreement between modeled and measured H_{rms} .

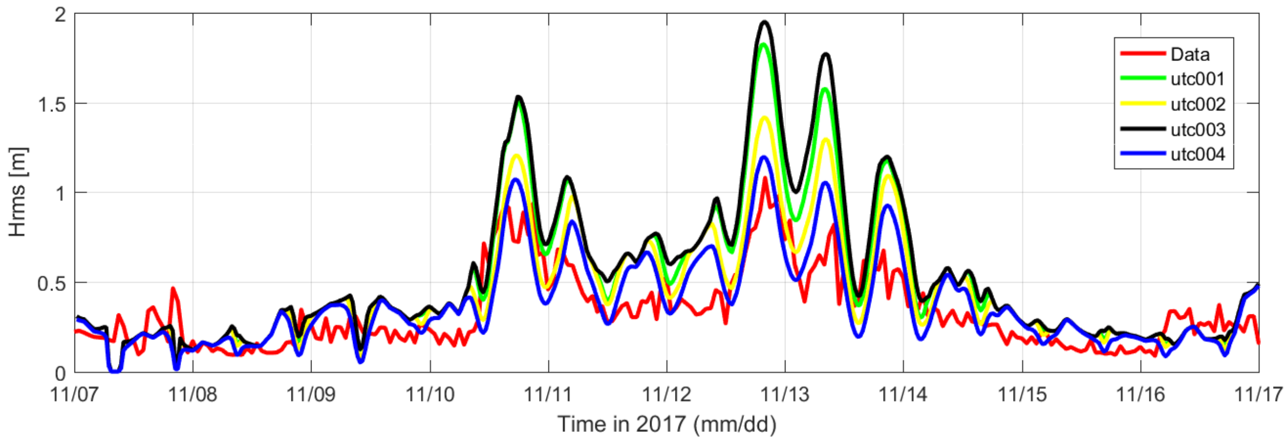


Figure 45 – Comparison of measured and computed wave height.

6.6 Influence of beach/shoreface nourishment on wave height

In this section, the influence of the beach and beach + shoreface nourishment on the wave height along cross-shore is investigated. This is done by conducting several simulations with different bed levels, representing for the cases of without nourishment, with beach nourishment and with beach + shoreface nourishment. In particular, six simulations were carried out with the following bed levels:

- Bed 1: Profile 100, measured in 2013: without nourishment
- Bed 2: Profile 100, measured in 2014: soon after beach nourishment
- Bed 3: Profile 100, measured in 2017: three years after beach nourishment
- Bed 4: Profile 104, measured in 2013: without nourishment case
- Bed 5: Profile 104, measured in 2014: soon after beach and shoreface nourishment
- Bed 6: Profile 104, measured in 2017: three years after beach and shoreface nourishment

In all simulations, the settings of run utc004 are applied.

The effect of beach nourishment on the wave height is found by comparing the wave height resulted from runs with Bed 1, Bed 2 and Bed 3. Similarly, by comparing the results from runs with Bed 4, Bed 5 and Bed 6, the influence of the beach and shoreface nourishment on the wave height will be evaluated. Two energic events with high waves during the calibration period are considered: one during high water and one during low tide. The water level (at Ostend) and wave condition (at Raversijde) of these events are:

- High water event: water level = 4.70 mTAW, H_{rms} = 2.0 m , Tp = 8.8 s, wave angle = -2° (or 327°N).
- Low water event: water level = 1.75 mTAW, H_{rms} = 1.55 m, Tp = 9.1 s, wave angle = -21° (or 346°N).

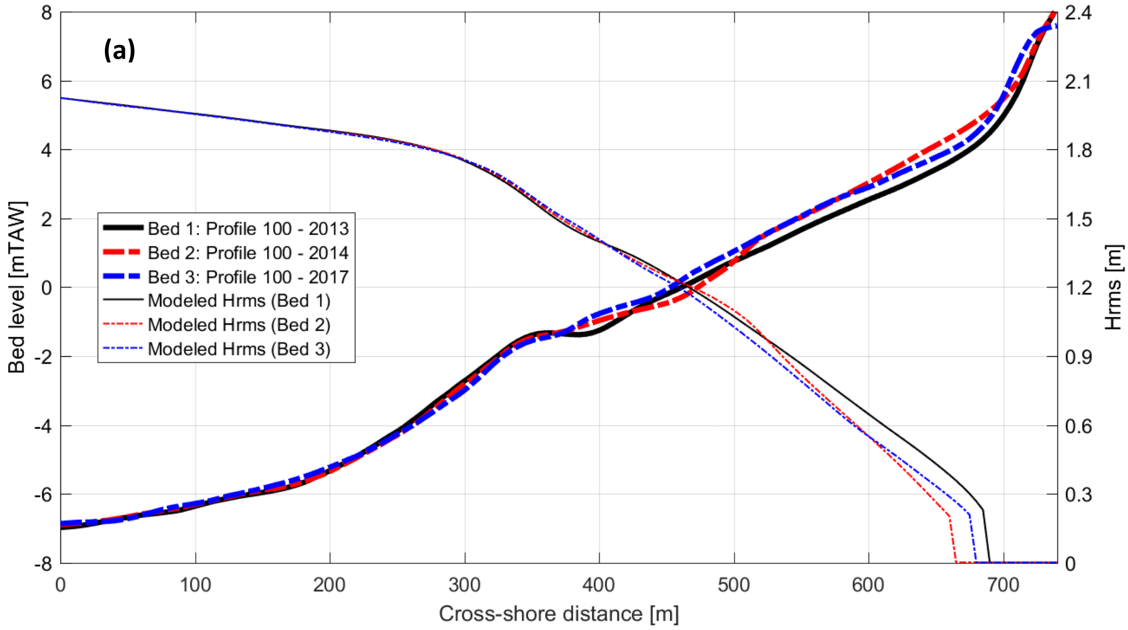
Figure 46 presents the comparison of the wave height along the cross-shore profile for the high water case for the runs with Bed 1, Bed 2 and Bed 3 (a); Bed 4, Bed 5 and Bed 6 (b). The corresponding results for the low water moment are presented in Figure 47.

As can be seen from Figure 46a for the case of beach nourishment, the reduction of the wave height occurs in the region of beach nourishment where the water depth is smaller. Over the three years after beach nourishment (2014-2017), there is only some minor changes of the beach level, causing little changes in the wave height in the area.

For the case of combined beach and shoreface nourishment (Figure 46b), the zone of wave height reduction extends further offshore where shoreface nourishment was carried out. The shoreface nourishment contributes to the reduction of the wave height in the zone 280 m – 480 m from the sea boundary; from 480 m onwards, the beach nourishment plays its role in reducing the wave height. For this event, the shoreface nourishment leads to a reduce in wave height up to 20 cm and maximum value of about 30 cm is calculated for beach nourishment.

The reduction of wave height is comparable for the case soon after and three years after shoreface nourishment. However, the location of maximum reduction for Bed 6 (in 2017) is shifted shoreward compared to case with Bed 5 (2014). This is the result of the shoreward migration of the (shoreface nourishment) sand bar in 2017, the water depth has been altered, causing the change in the wave height.

For the case of low water, the difference of the wave height is neglectable when using Bed 1, Bed 2 and Bed 3 (without, some months after and three years after beach nourishment) (Figure 47a). This is due to the fact that the beach is dry during low tide. For the case of shoreface nourishment (Figure 47b), this unfavorable condition (shallow condition) leads to a reduction of H_{rms} of 30 cm (25%) at the nourishment location. Again, the shift in location having maximum reduction of wave height is found for the year 2017 as the result of the shoreward migration of the sand bar three years after conducting shoreface nourishment.



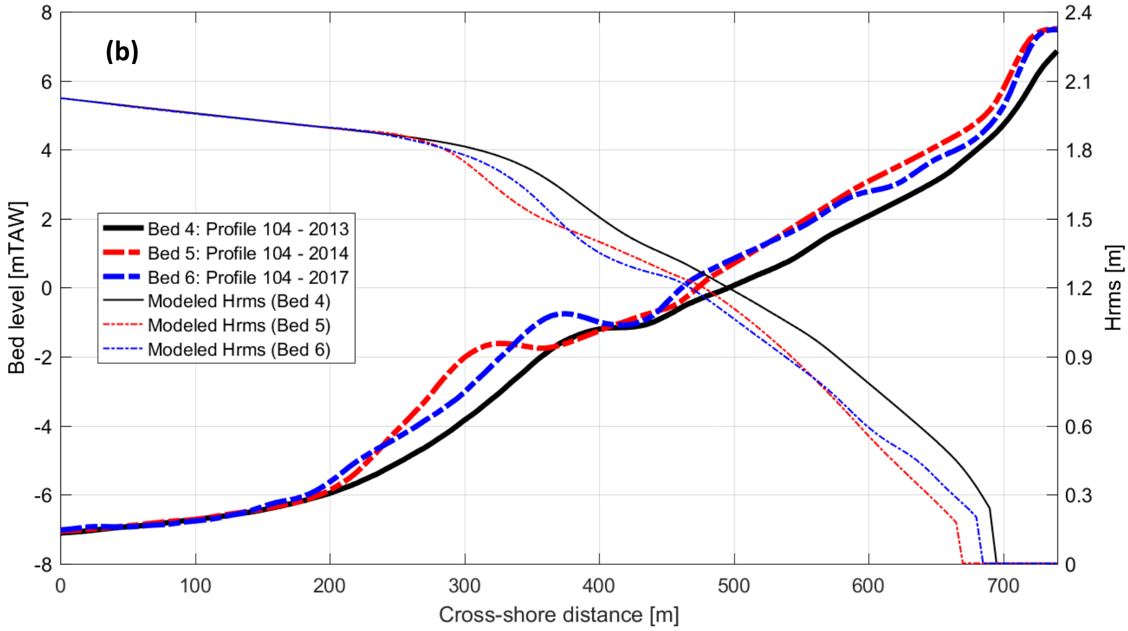


Figure 46 – Modeled H_{rms} with (a) profile 100 (without, soon after and three years after beach nourishment) and (b) profile 104 (without, soon after and three years after beach & shoreface nourishment) - High water.

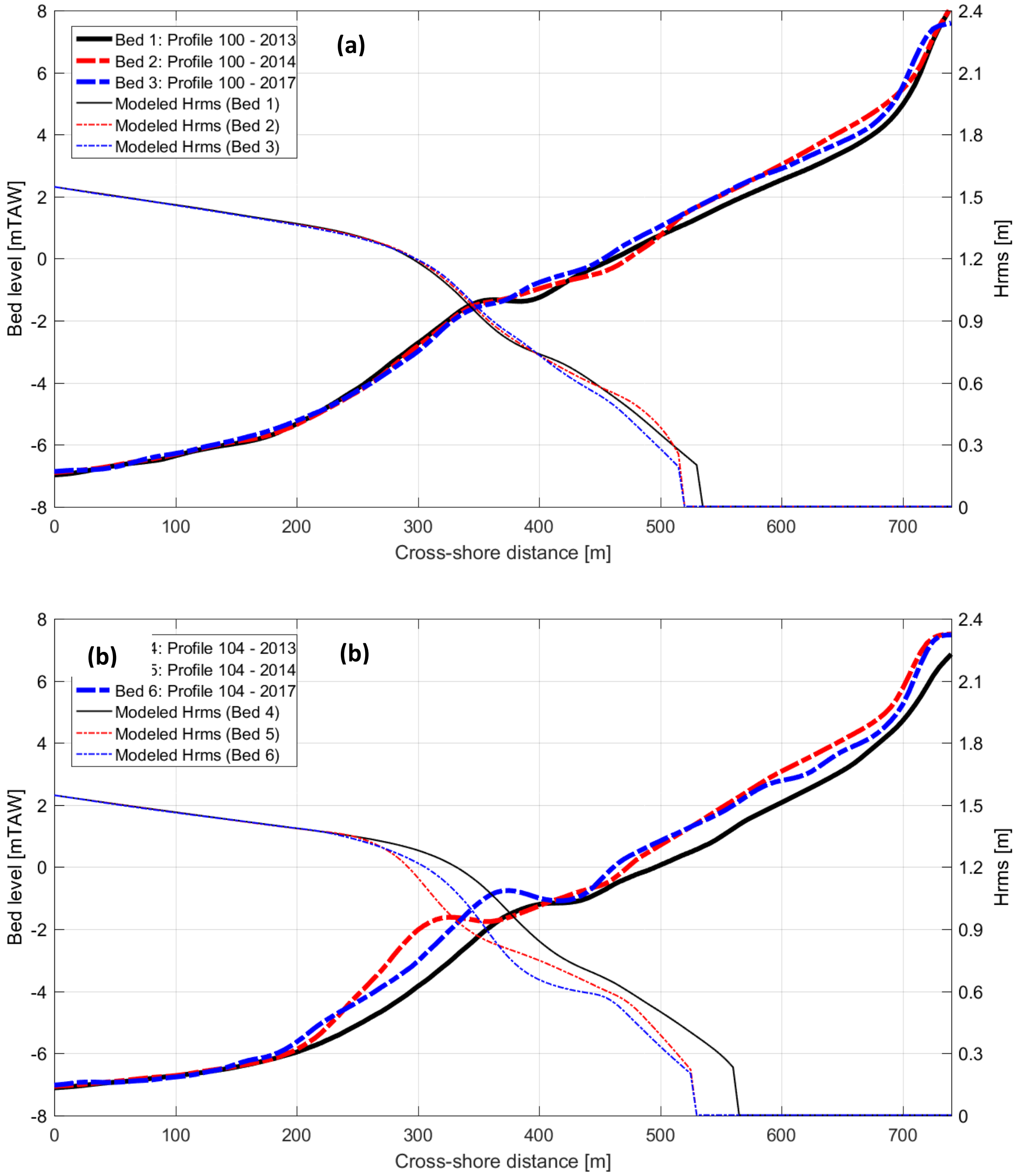


Figure 47 – Modeled H_{rms} with (a) profile 100 (without, soon after and three years after beach nourishment) and (b) profile 104 (without, soon after and three years after beach & shoreface nourishment) - Low water.

7 Conclusions

The present study investigated the evolution of a coastal nourishment experiment during the period 2013 and 2018. Two adjacent coast areas Raversijde and Mariakerke were supplied both with beach nourishment (sand deployed on the intertidal and dry beach) while the last also with a shoreface nourishment (placed on the submerged beach down to depths of -5.00 TAW). For a better understanding of sand dynamics two more areas neighbouring the experiment coast areas were considered, one situated downdrift, Middelkerke and one situated updrift, Ostend. The conclusions of the study will be presented and discussed below.

Evolution of the sand volumes deployed into the area.

The nourished sand at the entire study zone show generally low rates of erosion. The majority of the sand is still in the coastal system three years after the nourishments are carried out. The average efficiency three years after the nourishment is 77% for the three coastal zones where the nourishments were performed, decreasing in the direction of the alongshore transport from 97% at Raversijde to 73% at Mariakerke and 60% at Ostend. The estimation of the efficiency was limited to three years due to new nourishments which were performed in the area in 2018.

Possible explanations for the retention of the sand in the area are related to: 1) the accommodation space created at the downdrift side of the study area by the extension of the Ostend port; 2) the mild wave climate in the study area during monitoring period; 3) continuous human interventions at the study site by local redistribution of the sand on the intertidal and dry beach and by performing nourishments at the adjacent areas; 4) the grain size of the nourished sand being coarser than the local sediment.

However, not all the nourished sand can be found in the area and the possible explanations are related to: 1) further sand compaction after deployment; 2) various errors in measuring the volumes of sand, topo-bathymetric surveys and processing; 3) in particular for the Ostend area the accumulation of sand outside of the control box, defined for the pre-nourishment bathymetry (2013) - in the years following the sand accumulated in this area very rapid and enhance the transport around the port due to increasing shallower water depths; 4) losses of sand at the landward boundary (sand blown by the wind on the promenade or on the tramline) and at the offshore boundary of the study zone; 5) accommodation space created by the sea level rise during; the last two are quantitively minor, but still contributing to the total sand budget.

Evolution of different parts of the study zone.

The morphological evolution of the coastal areas after nourishment is showing rapid re-organisation of the sand. The intertidal beach has the most dynamic evolution due to the large amount of sand that was placed here and, due to the intense hydrodynamic forcing even during mild weather conditions and due to human interventions (beach levelling). The sand nourished on the shoreface at the Mariakerke evolved rapidly and while part of it migrated downdrift, most of it formed a submerged bar which stay approximately which moved predominantly landwards. The dry beach gained volume by aeolian transport supplying sand from the intertidal beach. The sea floor sector considered initially outside of the active beach displays a similar dynamics as the shoreface resulting in a new value for the closure depth at a yearly scale at approximately -6.00 m TAW.

Middelkerke area gains sand from the updrift adjacent area (large nourishment performed there), Raversijde keeps much of the relatively small volume of sand nourished here, Mariakerke area lost sand at a rather constant rate, Ostend area lost sand more rapid than the other sectors, mostly in the alongshore towards NE.

There are two clear migration patterns for the sand: cross-shore with tendency for the sand to accumulate on the dry beach and on the shoreface as a dynamic sand bar; and alongshore towards the Ostend port.

Although the volume difference maps indicate the dry and intertidal areas as being dynamic the analysis of the beach profiles carried out monthly for several year do not show any clear trend for the slope or width variation.

The comparison between the medium term and the short term evolution of the study area reveals that the erosive trends were reversed for most of the beach parts highlighting the stability of the nourishments. Three years after nourishment the trends are consistently positive and they are expected to maintain on medium term enhancing the coastal safety at the study zone.

Sediment transport

The cross-shore transport played a significant role on short term (probably months) in the local redistribution of the sand just after the nourishment, as indicated by migration of the sand bars at Mariakerke and Ostend area as well as relatively rapid redistribution of the sand nourished on the intertidal beach.

On the medium and long term the alongshore sediment transport is the main driving force for the evolution of the study zone. Several facts support this evidence: gain in sand volumes at Middlekerke area from the updrift area, relatively stability at Raversijde and accumulation of sand close to the Ostend port jetties.

The alongshore sediment transport was calculated for the area using the UNIBEST CL+ model and local wave data. When compared with the observed shoreline changes a net alongshore sediment transport ranging between 150 000 and 200 000 m^3/year is estimated as correct.

Shoreline position

Instead of analysing just position variation of a line which is often subject of errors, it was decided to use the concept of Momentary Coast Line which is a representation of a volume in the vicinity of the shoreline. The model was able to reproduce the Momentary Coast Line changes in position as measured in the field: migration towards the sea for all three nourished areas in ranging from several metres in the southern part of the Raversijde and in the central part of Ostende area to tens of metres for the rest of the sections, excepting Middelkerke.

Simulation of the Momentary Coast Line position for the future 9 years, assuming absence of the human interventions, indicates advance in the first part and erosion for the second half of Middelkerke area, mostly advance at Raversijde, predominantly retreat at Mariakerke and mostly accumulation at Ostend strongly increasing towards the port jetty. These results confirm the Mariakerke area as most prone to erosion when compare to the adjacent areas, but also that the accommodation space created at Ostend by the port jetties' extension which will probably keep on accumulating sand.

Reference sections

Sections 100 and 104 situated at Raversijde and Mariakerke, respectively were selected for comparison between different types of nourishment. Both section indicate accumulation respect to the situation pre-nourishment, but in the case of Mariakerke the shoreface nourishment is clearly visible as a submerged sand bar which migrates back and forth, but at a location closer to the shore than the initial deployment. At Mariakerke, section 104, the entire active beach is more dynamic as a consequence of the larger volume of sand nourished here. Three year after the nourishment elevation of the profile 104 increased more than in the case of section 100, Raversjide, clearly increasing the safety against the severe storms.

Protection of the shoreface nourishment against coastal flooding.

The submerged sand bar formed as the results of the shoreface nourishment can reduce the wave height during storm events, both during low and high tide. The simulations using UNIBEST TC clearly show a large reduction of the wave height on the profile 104 (with both beach and shoreface nourishments) and a smaller reduction on the profile 100 (just beach nourishments).

Efficiency of the shoreface nourishment

The shoreface nourishment provides a certain protection against flooding by decreasing the wave height during different wave conditions. The shoreface nourishment is rather stable, most of the initial volume being still in place after three years. After a rapid loss the volume of the submerged bar seems to stabilize and fed with sand by the adjacent areas.

A very precise estimation of the shoreface nourishment is difficult to be done due to many influences on the study zone such as nourishments performed in the vicinity or inside of the study zone during the experiment and re-distribution of the sand on the dry and intertidal beach performed by the local authorities before summer and before winter. However, the shoreface area shows a large increase in volume when compared with the pre-nourishment situation and much lower rates of erosion than during the decade before.

An indirect positive influence on the safety of the coast generated by the shoreface nourishment is the increase of the active beach volume. As a strong storm decrease the safety level of the beach a larger sand volume at shoreface is available for the rebuilding of the aerial and intertidal beach during calmer periods.

A shoreface nourishment is a good measure for coastal protection and its protection effects is clear on medium term and probably also on long term. The safety against extreme storms, such as the one with the return period in 1000 year was not estimated in the current project since a different project will investigate this for the entire Belgian coast. To meet all the safety criteria at the Belgian coast it is recommended to use the shoreface in combination with the beach nourishment because the shape of the entire active beach profile is influencing the probability of the flooding.

8 Recommendations

Based on the analysis of the pilot beach and shoreface nourishment at area Rversijed – Mariakerke and and then extended to larger area Middelkerke – Ostend a series of recommendations can be formulated:

Monitoring and research

Although the analysis of the nourishments clearly described the volume changes at different beach parts, the proportion between sediment transport along- and cross-shore it is not clearly understood. This can be addressed using various 1D and 2D process based numerical models such as XBeach, UNIBEST CL+, Deltf3D, Telemac etc.

For various coasts worldwide, a 1D profile based approach for coastal monitoring is adopted due to the lack of detailed measurements. However, at the Belgian coast a 2D approach, using sediment budgets for the entire interest nearshore domain can be adopted since large datasets are available. A better understanding of the sand circulation can be achieved for such a complex coast.

Monitoring of the area should continue as the nourishments continue their evolution for many years. No complex measurements are required, but the standard topographic and bathymetric measurements which are already carried out yearly by Coastal Division and analysis of the volume changes for different active beach parts.

At large time scales (decadal) exchange of sand between the nearshore system and the coastal sand banks is possible and this cannot be numerically simulated using the current coast models. Limitation are related to both the capacity of the numerical models and the complex bathymetry of the Belgian coast.

At yearly time scale the concept of closure depth is useful and it better derived by analysis of the bathymetric maps rather than calculated using the largest waves recorded and the local grain size.

At very short time scale (days, weeks) the erosive effect of the storms can be evaluated using numerical models such as XBeach, but the rebuilding of the intertidal and dry beaches by sand transported from the shoreface area during calmer periods cannot be numerically reproduced. Field measurements, as profiles for the entire active beach (dune foot/sea wall to the closure depth) should be measured before, immediately after significant storms and few weeks later. The analysis of these measurements can establish how fast a beach is recovering and how much of the eroded sand volume returns to the intertidal and dry beach from the shoreface.

Grain size of the sand as it differs on various parts of the beach is very important because it is influencing the beach slope and stability and, on the longer term, the efficiency of the nourishments. It is recommended that the sand used for nourishment is sampled both in situ at the extraction area and on the ship before deployment. For a better understanding of the post-nourishment sand circulation it is recommended that a grain size map is built before the nourishment and 3 to 5 years after the nourishment. As the grainsize varies rather cross-shore than alongshore a profile sampling approach can be adopted.

Nourishments execution

The present study show that the nourishment volume erode at low rate when the area is confined by a relative impermeable obstacle such as the port jetties. The sand circulate alongshore in the direction of the net alongshore current, from SW to NE, and this have to be accounted when the nourishment is designed. A concrete example is the nourishment in front of the city of Ostend where in the design should be accounted also for the sand transported by alongshore current from the nourishments performed updrift.

A feeder type approach can be adopted in the future for design of the coastal nourishments. Sand should be placed in the areas with the largest alongshore transport, accounting for dissipation in the direction of the net current and thus feeding the vulnerable beach sectors for several years, probably increasing the efficiency of a nourishment.

Selection of the cross-shore beach part for a nourishment is also important as the present study determined. The dry beach tends to accumulate sand from the intertidal zone, most probable transported by the wind, so the volume of sand nourished here should be kept at minimum. The intertidal beach is the area with the fastest rate of erosion, sand from here migrating not just to the dry beach but mainly to the shoreface. The shoreface nourishments are rather stable and they can be used in combination with beach nourishments to strengthen the beach resilience against severe storms.

When the coastal safety is considered at decadal time scale, for instance 2020 to 2050, the accommodation space created by the sea level rise and the local subsidence is significant. If the active beach has enough sand available, it will probably adapt to the new sea level. Shoreface nourishments are an appropriate method to realize this growth of the sandy sea defense with sea level rise. Sand deployed at the lower part of the profile will redistribute due to natural dynamics across the entire active profile increasing the beach resilience.

9 Bibliography

Bertels, L., Houthuys, R., Deronde, B., Janssens, R., Verfaillie, E., Van Lancker, V., 2012. Integration of optical and acoustic remote sensing data over the backshore-foreshore-nearshore continuum: a case study in Ostend (Belgium). Journal of Coastal Research, 28(6), 1426-1436.

Coastal Safety Masterplan. 2011.http://afdelingkust.be/sites/default/files/atoms/files/Masterplan%20Kustveiligheid.pdf

Dan, S., Silva, R., Montreuil, A-L., Verwaest, T., Mostaert, F., 2016. Coastal Morphology at Mariakerke: Report D3+D4: Report D3+D4: Changes, evolution, trends and indicators for the period 2015-2017. Version 4.0. FHR Reports, 16_000_1. Flanders Hydraulics Research: Antwerp.

Dan, S.; Vandebroek, E. (2017). A sediment budget for a highly developed coast - Belgian Case, in: (2017). Coastal Dynamics 2017. Paper no. 134

Deltares, 2011. UNIBEST-CL+ manual: Manual for version 7.1 of the shoreline model UNIBEST-CL+

Deronde, B., 2007. The sediment dynamics along the Belgian shoreline, studied with airborne imaging spectroscopy and LIDAR. PhD Thesis. Universiteit Gent. 204 pp

Houthuys, R., 2012. Morfologische trend van de Vlaamse kust in 2011. Agentschap Maritieme dienstverlening en Kust. Afdeling Kust.

Houthuys, R.; Verwaest, T.; Dan, S.; Mostaert, F., 2020. Morfologische evolutie van de Vlaamse kust tot 2019: WL Rapporten, 18_142. Waterbouwkundig Laboratorium, Antwerpen (in Dutch, in preparation).

Ministerie van verkeer en waterstaat, 1991. "De basiskustlijn, een technisch / morfologische uitwerking" (in Dutch).

Montreuil, A-L.; Chen, M.; Brand, E.; Strypsteen, G.; Rauwoens, P.; Vandenbulcke, A.; De Wulf, A.; Dan, S., and Verwaest, T., 2018. Dynamics of surface moisture content on a macro-tidal beach. In: Shim, J.-S.; Chun, I., and Lim, H.S. (eds.), Proceedings from the International Coastal Symposium (ICS) 2018 (Busan, Republic of Korea). Journal of Coastal Research, Special Issue No. 85, pp. 206–210. Coconut Creek (Florida), ISSN 0749-0208.

Silva, R.; Montreuil, A-L.; Delgado, R.; Dan, S.; Chen, M.; Mostaert, F. (2016a). Coastal Morphology at Mariakerke: Report D1: Changes, evolution and trends, indicators and Argus monitoring. Version 2.0. FHR Reports, 00_128_7. Flanders Hydraulics Research: Antwerp.

Silva, R., Dan, S., De Maerschalck, B., Verwaest, T., Mostaert, F. (2016b). Short term morphological effects at Mariakerke: Report D2: Morphological numerical modelling – Xbeach. Version 4.0. FHR Reports, 00_128_12. Antea Group & Flanders Hydraulics Research: Antwerp.

Vandebroek, E.; Dan, S.; Vanlede, J.; Verwaest, T.; Mostaert, F. (2016). Sediment budget for the Belgian coast, FHR reports, 12_155: Antwerp, Belgium. 101 pp.

Walstra, D.J.R. (2000). Unibest-TC Userguide, WL | Delft Hydraulics.

Appendix 1 LIDAR surveys processing

The LIDAR datasets are composed of XYZ points (X, Y in Lambert 72 georeferenced system and Z elevation in TAW vertical system). Although the surveys of the emerged beach are conducted in the same approximate locations, there are small differences in their coverage. Usually, their seaward limit is the water line, whilst the inland limit is variable. Thus, the covered area changes as a function of the water line position by the time of the survey and the adopted inland limit.

The first step in processing the datasets was the delimitation of the areas covered by the surveys, extending from the waterline limit to the inland limit coincident with the dike, where it exists. For each survey, a polygon was delineated in ArcGis (Figure 48). The datasets were interpolated, using the nearest neighbor interpolation method, to DEM's with 2 m resolution and then clipped using these polygons (Figure 49).

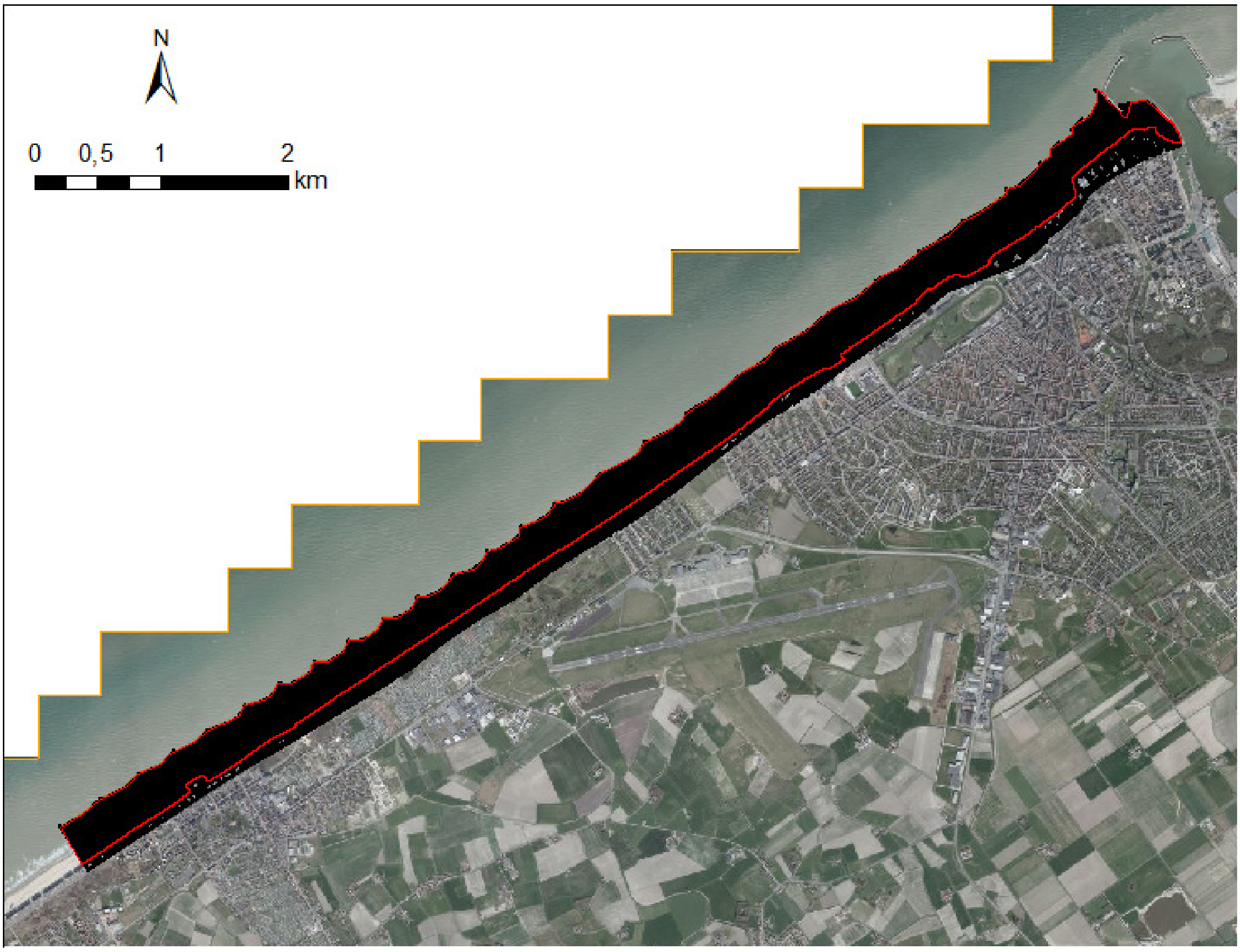


Figure 48 - Example of a LIDAR dataset and the delineated polygon for the study area (survey conducted in 27/10/2015).

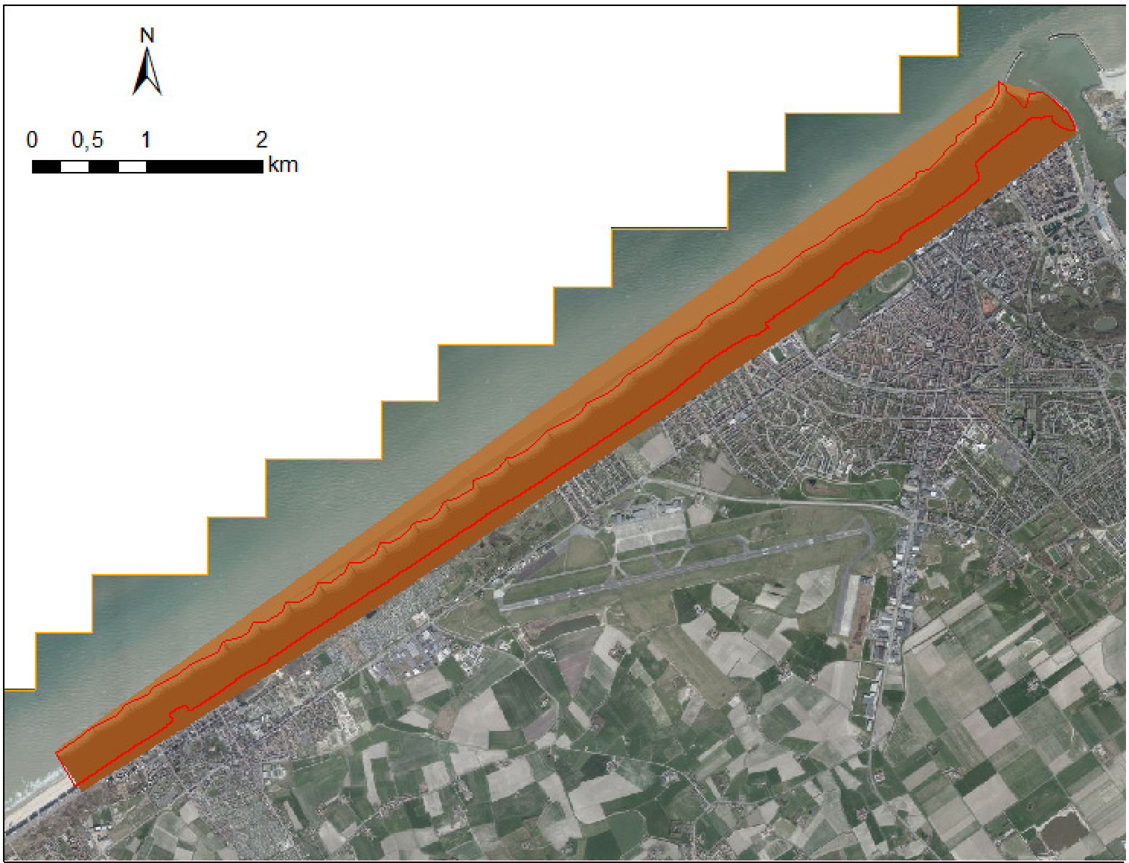


Figure 49 - Example of the delineated polygon over the interpolated DEM (above) and clipped DEM (below) (survey conducted in 27/10/2015).

Appendix 2 Single- and multi-beam surveys processing

The single- and multi-beam datasets are composed of XYZ points (X, Y in Lambert 72 georeferenced system and Z elevation in TAW vertical system). Although the surveys are conducted in the same approximate locations, there are differences in the surveys' coverage.

The first step in processing the datasets was the delimitation of the areas of coverage, by delineating the limiting polygon (Figure 50). The surveys were first interpolated to a TIN (Triangulated Irregular Network) and then converted to 10 m resolution raster datasets. The delineated polygons were used to clip the corresponding rasters (Figure 51).

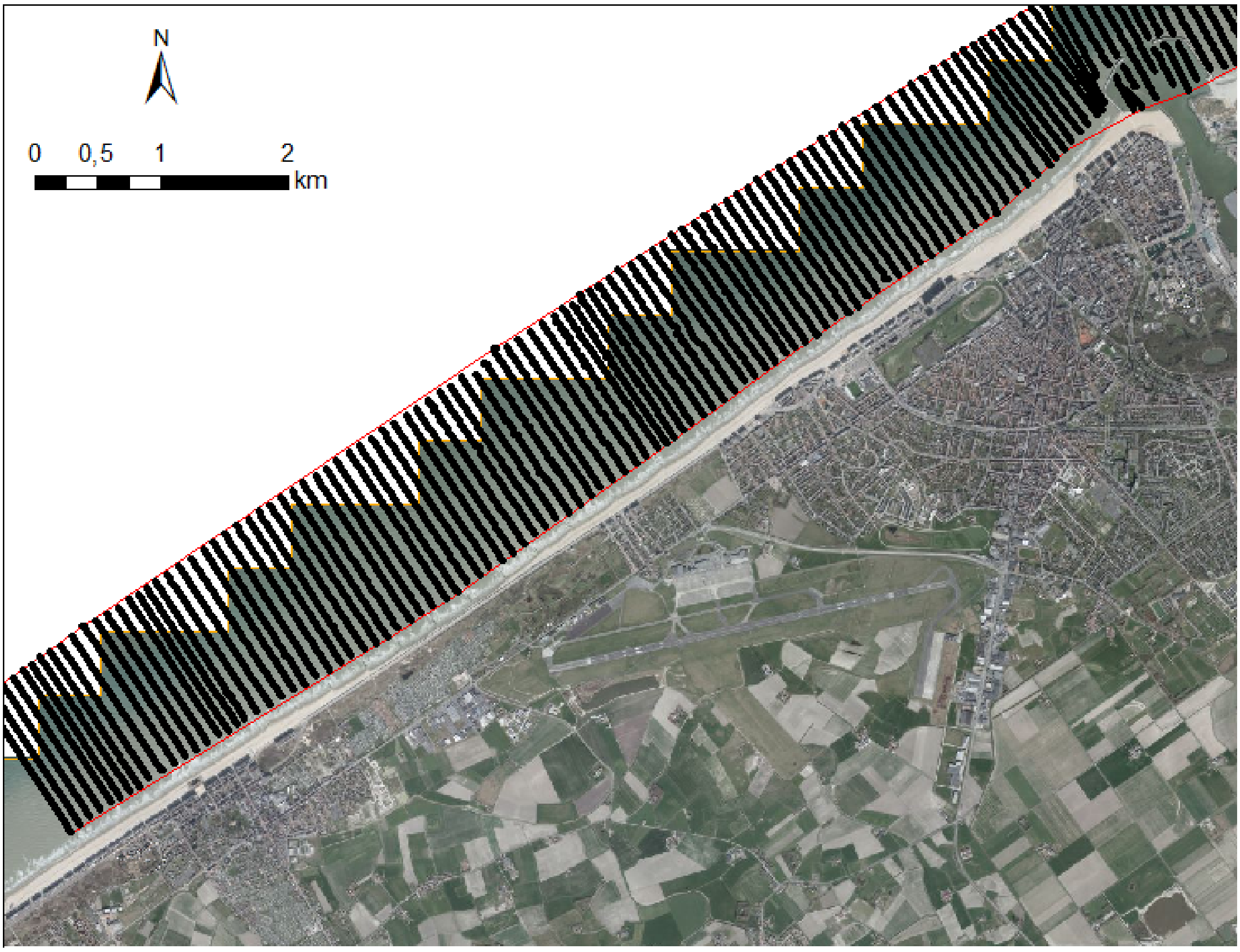


Figure 50 - Example of a single-beam dataset and the corresponding delineated polygon for the study area (survey conducted in 04/06//2015).

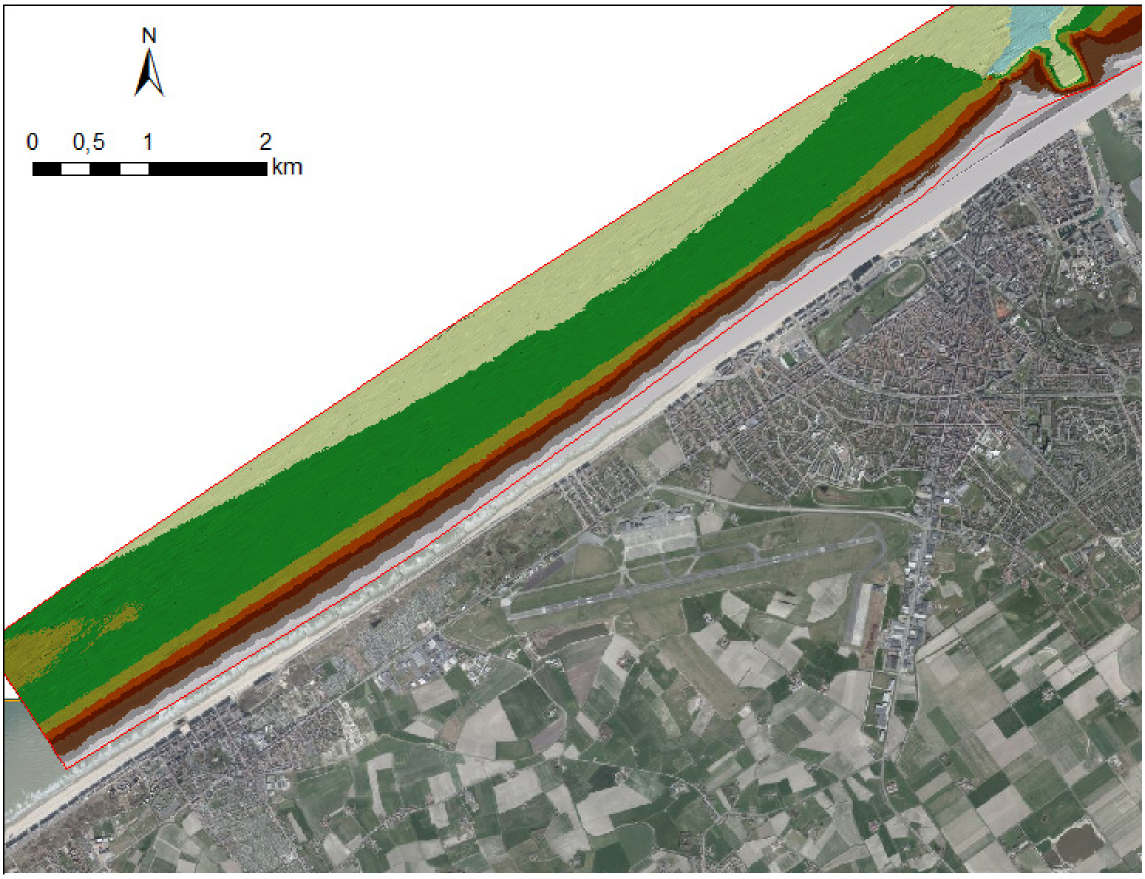


Figure 51 - Example of the delineated polygon over the interpolated TIN (above) and clipped raster (below) (survey conducted in 04/06/2015).

DEPARTMENT **MOBILITY & PUBLIC WORKS**
Flanders hydraulics

Berchemlei 115, 2140 Antwerp
T +32 (0)3 224 60 35
F +32 (0)3 224 60 36
waterbouwkundiglabo@vlaanderen.be
www.flandershydraulics.be